Micro-optical force sensor concept based on whispering gallery mode resonators

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Received 18 March 2008; accepted 9 April 2008; posted 24 April 2008 (Doc. ID 93940); published 22 May 2008

A micro-optical force sensor concept based on the morphology-dependent shifts of optical modes of dielectric microspheres is investigated. The optical resonances, commonly referred to as the whispering gallery modes (WGM), were excited by evanescently coupling light from a tunable diode laser using a tapered single-mode fiber. A compressive force applied to the sphere induces a change in both the shape and the index of refraction of the sphere leading to a shift in WGM. By tracking the shifts, the force magnitude is determined using solid silica as well as solid and hollow Polymethyl-methacrylate (PMMA) microsphere resonators. A measurement sensitivity as high as \(\frac{d\lambda}{dF} = 7.664 \text{ nm/N} \) was demonstrated with a 960 \( \mu \text{m} \) hollow PMMA sphere. © 2008 Optical Society of America


1. Introduction

Optical microcavity resonators have attracted interest due to their unique properties including the very high quality factors, \( Q = \lambda / \delta \lambda \) (where \( \lambda \) is the laser wavelength and \( \delta \lambda \) is the observed resonance linewidth), they can exhibit. The resonances are commonly referred to as the whispering gallery modes (WGMs) and \( Q \)-factors as high as \( 10^9 \) have been reported in the literature [1]. In recent years, WGM applications have been explored in communication (switching, filtering, and multiplexing) and sensor technologies [4]. The WGM resonances are highly sensitive to morphological changes (such as the size, shape, or refractive index) of the resonance cavity and they can be tuned by causing a minute change in the physical condition of the surrounding. Conversely, changes in the environment surrounding the sphere can be determined by monitoring the WGM shifts. For example, the temperature [3] and pressure [4] tuning of the WGM of dielectric spheres demonstrated their potential for switching applications. Several WGM-based microcavity sensor concepts have also been considered for biological and chemical applications including those for protein detection [5–7], trace gas detection [4], impurity detection in water [4], and temperature sensing [10]. In the area of mechanical sensing, a WGM-based accelerometer has been demonstrated [11].

Measurement of mechanical strain using WGM resonances was demonstrated first in 1993 [12]. In this work, a 1 mm length section of a 125 \( \mu \text{m} \) diameter single-mode silica optical fiber was used. The cylindrical microresonator was strained using a PZT-driven vise that was attached to the resonator. The free-space beam of a tunable Ti:sapphire laser (~700 nm) was focused on the cylinder at a grazing angle and its WGM were monitored through the elastically scattered spectrum. A WGM shift of ~0.8 nm was observed for a strain of ~5.8 \times 10^{-3}. The reported quality factor for the typical WGM was \( Q \approx 10^5 \). In a later study, the mechanical strain-induced WGM shifts of microspheres with higher \( Q \)-factors were investigated [13]. In this
study, compressive force was applied to a 160 \mu m diameter microsphere. The WGM of the sphere were excited by an external-cavity diode laser operating in the near IR (\sim 807 nm) whose output was evanescently coupled to the sphere using a prism coupler. A WGM quality factor of \( Q \sim 10^5 \) and a strain tuning range \( \Delta \lambda > 0.3 \) nm were obtained. Estimates presented in [13] indicate that deformations of sphere as small as 0.01 nm can be detected with the reported \( Q \)-factor (This is assuming that the resolution is determined by the resonance linewidth. In practice, a shift of a fraction of the linewidth could be resolved further increasing the strain resolution.) Such levels of strain resolution raise the possibility of high-sensitivity gauges that measure force virtually without any deformation of the sensing element. This feature is unique to WGM technology and attractive to a number of applications.

The studies reported in [12][13] demonstrated force tuning of silica microresonators. However, the elastic modulus of silica is relatively high and, therefore, may limit the applicability of a WGM-based force/stress sensor to problems that require high sensitivity. Measurement sensitivity can be improved by using dielectric materials with smaller elastic modulus, such as polymers, and using hollow resonators. In the above-mentioned work [13], a microsphere was coupled to the optical fiber using a prism. Coupling of the spheres directly to the carrier (fiber) [4] is technically simpler and thus more likely to have a broader set of applications including embedded and distributed sensors.

In the present effort, we examine the feasibility of WGM-based force sensing for which the microspheres are coupled to optical fibers to interrogate their WGM. The force-induced WGM shifts of fused silica and Polymethyl-methacrylate (PMMA) spheres are measured and related to the applied force (we note here that in the above-mentioned experiments the magnitude of the force causing WGM shift was not measured). Using various microsphere sizes, materials, and geometry (solid and hollow), a range of sensitivity is demonstrated.

While microresonators of various shapes produce WGM, this study focuses on the spherical shape due to (1) the simplicity of obtaining relatively large \( Q \)-factor resonances in comparison, for example with cylindrical resonators, and (2) the large number of resonances in the spectrum that makes continuous tracking of WGM easier for a longer range. In a conceptual force sensor (see Fig. 1), the microsphere sensing element, with a diameter of several tens to several hundreds of micrometers, is weakly coupled to an optical fiber that carries light from a tunable laser and serves as an input/output port for the microsphere. On the output end of the fiber, the transmission spectrum is monitored by a photodiode (such as shown in Fig. 2). As the laser is tuned, the WGM of the sphere are excited leading to dips in the fiber transmission spectrum. A compressive force applied along the polar direction, as shown in Fig. 1, perturbs both the equatorial radius and the refractive index of the sphere, thus changing the WGM wavelengths. By monitoring the induced WGM shifts, the magnitude of the applied force is determined. Note that the typical deformations that induce readily measurable resonance shifts are of the order of nanometers and, hence, there are essentially no moving parts associated in this force sensor concept.

The condition of optical resonance is met when the optical path length to complete a round trip in the sphere is a multiple integer of the light wavelength, \( \lambda \). That is, \( 2 n r_e n = l \lambda \) where \( r_e \) and \( n \) are the equatorial radius and refractive index of the sphere, respectively, and \( l \) is an integer representing the order number of the resonance. The above equation holds for \( l \gg 1 \). A change in \( r_e \) and \( n \) will cause a change in the resonant wavelength:

\[
\frac{dr_e}{r_e} + \frac{dn}{n} = \frac{d\lambda}{\lambda}.
\]

A force applied to the microsphere along the polar direction (Fig. 1) will result in strain in the equatorial plane (\( dr_e \)), causing a shift in the resonant wavelength, \( d\lambda \). Mechanical stress would also affect the refractive index of the material. The extent of the stress effect is determined by the elasto-optic properties of the sphere. For both silica and PMMA, normal tensile stress produces \( dn < 0 \).

2. Experimental Details

A. Fabrication of Sensing Elements

To achieve efficient optical coupling between the sphere and the fiber, the evanescent field outside the fiber needs to be expanded. It could be done by eroding a part of the fiber [12] or by stretching a portion of the fiber (with cladding) under heat [16]. A microtorch was used in the present work to prepare a stretched section of the fiber (with a minimum diameter between 5 and 10 \( \mu m \)) such as that shown in Fig. 4.

Fig. 1. (Color online) Microsphere under compressive force. \( r_e \) and \( r_o \) are the equatorial and polar radii.
Silica and PMMA spheres were manufactured using two different approaches. The silica microspheres were made by melting one end of a short section of the optical fiber (including the cladding) with a micro-torch. The flame temperature and duration controlled the size of the sphere that forms at the tip of the fiber. The stem allows for easy manipulation of the microsphere. In the first set of experiments, the solid PMMA spheres were manufactured by first melting polymer powder (with a particle size of a few micrometers) in a container placed in a hot oil bath at a temperature just above the PMMA melting point ($\sim 150^\circ C$), then stretching the PMMA fibers, with diameters of 125 micrometers or smaller, as it solidified, and, finally, melting the tip of the cooled fiber through radiative heating. The $Q$-factors for the PMMA sensors prepared this way were found to be smaller than those for silica spheres ($\sim 5 \times 10^4$ as compared to $> 10^6$ for silica) most probably due to impurities in the material and surface irregularities caused by uneven heating. We improved the $Q$-factors for the PMMA microspheres to better than $10^6$ by using a different fabrication process.

In this process, impurities in the polymer were removed by first dissolving it in chloroform and then adding it to a solution of methyl alcohol where the polymer precipitates. The material is next passed through a paper filter. The purified PMMA (trapped in the filter) is again dissolved in chloroform and then, using a microsyringe, a controlled drop of it is placed at the tip of a PMMA fiber. The hollow PMMA spheres were obtained by injecting a controlled amount of air into the liquid polymer before depositing it onto the fiber stem. Figure 4 shows photographs of typical silica and PMMA spheres.

B. Experimental Setup

A schematic of the optical system is given in Fig. 2. The output of a distributed feedback (DFB) tunable 1312 nm diode laser with nominal power of 5 mW is coupled to a single-mode optical fiber. A portion of the laser light (about 10% of the total intensity) is extracted through a splitter to monitor its intensity as its frequency is tuned. Both the reference and the 90% intensity signal fibers are terminated at photo diodes (PDs). The DFB laser is current-tuned using a laser controller that also keeps the laser diode’s temperature constant. The controller is driven by a function generator which provides a saw-tooth voltage output. The two PD outputs as well as the function generator output are sampled using a 16 bit data-acquisition card and processed by a host computer. The reference PD output is used to normalize the spectrum from the sensor fiber. The host computer performs the scanning, data acquisition, and analysis. A software module, developed in-house, identifies the WGM and monitors their shifts. It provides a reliable and fast fit to an experimental WGM spectrum and enables a continuous tracking and recording of resonance shifts in real time.

Force is exerted on the microsphere using two hardened stainless steel pads that compress the sphere along the polar direction as shown in Fig. 5. One of the pads is driven by a microtranslation stage and is connected to a load cell that measures the applied force. Two different load cells (with force range of 1.5 N with a resolution of $10^{-2}$ N and with the range of 0.1 N with a resolution of $10^{-4}$ N) are used for silica and PMMA spheres, respectively.

A set of raw WGM spectra obtained for a solid and a hollow PMMA sphere is shown in Fig. 6. In this experiment, microspheres are compressed by the pads and the transmission spectra are recorded for several consecutive values of the applied force. The spheres are preloaded and $\Delta F$ represents increments to this preload value. As the applied force increases, the resonances shift in the positive direction (the resonant wavelength increases with increasing compressive force). In both cases, the initial $Q$-factor is $\sim 10^6$. A decrease in the $Q$-factor is observed with increasing force, especially for the hollow sphere. This effect can
be attributed to a number of physical changes including a perturbation in the sphere–fiber spacing.

3. Results and Discussion

A large number of spheres with diameters ranging between 300 and 980 μm were made and tested as force sensing elements. As an example, Fig. 7(a) shows the compression loading and unloading cycles of a solid silica sphere. Here zero force corresponds to a certain preload value. The sphere diameter for this experiment was ~350 μm with a Q-factor of ~10^6. There is excellent correlation between the WGM peaks tracked by the recognition software (shown as symbols) and the corresponding load cell signal (solid line). Under repeated compression and decompression training of the microsphere, the observed WGM shifts demonstrate a linear response with no discernible hysteresis in the load range tested, thus providing a reliable force reading essential for sensor performance. The corresponding resonance shift as a function of the applied force (load cell signal) is plotted in Fig. 7(b). Note that in all force measurements discussed here, including in Fig. 7, the temperature of the environment surrounding the sensor is kept constant in order to avoid the additional effect of temperature on resonance shifts.

Figure 8 compares the performance of a solid silica sphere to those for a solid PMMA and a hollow PMMA...
sphere. The diameters of the solid silica, solid PMMA, and the hollow PMMA spheres are 430, 470, and 960 \( \mu m \), respectively. The average wall thickness of the hollow sphere was \( \sim 20 \mu m \) (determined under a microscope). In all three cases, the WGM shift, \( \Delta \lambda \), was essentially a linear function of applied force in the range studied. Also, the compression and decompression cycles were nearly identical indicating no discernible hysteresis. The slope of the plot (\( d\lambda/dF \)) for the solid PMMA is greater than that for the silica sphere owing to the fact that the elastic modulus for the PMMA (\( \sim 2.5 \) GPa) is smaller than that for silica (\( \sim 70 \) GPa). (Table 1 summarizes the properties of the two materials.) The PMMA force measurement is more sensitive than silica. However, the maximum force that the PMMA sphere can sustain within the elastic limit is smaller than that for silica, making the dynamic range of PMMA-based sensing narrower.

A separate experiment was carried out to determine the possible long-term degradation of PMMA spheres under load. In this study, the compression and decompression portions of the measurements of a solid PMMA sphere were carried out five days apart. The sphere was first compressed and left with the load on for a duration of five days before the decompression portion of the measurement was carried out. The difference in \( d\lambda/dF \) slopes for the compression and decompression cycles were less than 7%, indicating little or no deterioration of the sphere properties at least over the period considered. The maximum applied load was 0.07 N for this study.

The measurement resolution, \( \delta F \), defined here as the force required to shift the WGM by an amount of the WGM dip line width, \( \delta \lambda \), is \( \delta F = \frac{1}{Q} (\frac{d\lambda}{dF})^{-1} \). Assuming \( Q = 10^9 \), one may estimate force resolutions of \( \sim 5 \times 10^{-2} \) N, \( \sim 1 \times 10^{-3} \) N, and \( \sim 10^{-4} \) N for the solid silica, solid PMMA, and hollow PMMA data of Fig. 8, respectively. Better sensitivities could be achieved in practice if shifts smaller than the linewidth are resolved.

The sensitivity of the sensors depends on the size of the microsphere. To calibrate for size, a number of silica and PMMA microspheres of various diameters were manufactured and force-tuned to obtain plots similar to those shown in Fig. 7(b). The variation of the slope, \( d\lambda/dF \), with sphere diameter, \( D \), for solid silica and solid PMMA are shown in Fig. 9.

![Fig. 8. WGM shift as a function of applied force for silica and PMMA spheres.](image)

![Fig. 9. Force sensitivity dependence on diameter for solid (a) silica and (b) PMMA microspheres.](image)

**Table 1. Material Properties of Silica and PMMA**

<table>
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<tr>
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<th>Fused Silica</th>
<th>PMMA</th>
</tr>
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<tbody>
<tr>
<td>Index of Refraction</td>
<td>1.447</td>
<td>1.492</td>
</tr>
<tr>
<td>Thermal Expansion Coef.</td>
<td>5.5 \times 10^{-7}/°C</td>
<td>6.6 \times 10^{-5}/°C</td>
</tr>
<tr>
<td>Thermal Refractive Index Coef., ( dn/dT )</td>
<td>10^{-5}/°C</td>
<td>( -10^{-6}/°C )</td>
</tr>
<tr>
<td>Young Modulus E(GPa)</td>
<td>73</td>
<td>1.8–3.1</td>
</tr>
<tr>
<td>Compressive Strength (GPa)</td>
<td>1.108</td>
<td>0.07–0.14</td>
</tr>
<tr>
<td>Yield Strength (GPa)</td>
<td>3–4</td>
<td>0.02–0.05</td>
</tr>
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corresponding calibration curve for the hollow PMMA spheres (with a constant wall thickness of \( \sim 20 \mu m \)) is presented in Fig. 10. The function fits through each data set are presented as dashed lines in the figure. The sphere diameters were determined using a digital microcaliper. The uncertainty in the measured diameter was dominated by the caliper sensitivity which was \( \sim 13 \mu m \) and the uncertainty in the slope was approximately 3%. All the measurements in each calibration were carried out at the same ambient temperature.

If the shapes of the spheres manufactured in different sizes are nearly identical, for a given material and laser wavelength, the sensitivity is solely determined by the elastic deformation limit of the material. It is shown that the sensitivity is solely determined by the caliper sensitivity which was \( \sim 13 \mu m \) and the uncertainty in the slope was approximately 3%. All the measurements in each calibration were carried out at the same ambient temperature.

If the shapes of the spheres manufactured in different sizes are nearly identical, for a given material and laser wavelength, the sensitivity \( \frac{d\lambda}{dF} \), is dependent only on the diameter of the sphere. Therefore, with the above assumptions, for a given sphere material, shape, compression method, and laser wavelength, each individual sensor does not have to be independently calibrated. Once “universal” calibration such as those shown in Fig. 6 is performed, all that needs to be known is the diameter of the sphere, which essentially provides the measurement sensitivity (or “gain”) for the sensor.

4. Conclusions

A micro-optical force sensing concept that is based on the morphology-dependent shifts of resonant optical modes of silica and PMMA spheres is demonstrated and measurements were carried out to characterize the concept for spherical microlasers ranging between \( \sim 300 \) and \( 950 \mu m \) in diameter and made of silica and PMMA materials. Force resolution of the order of \( 10^{-3} \) N was demonstrated with solid silica spheres of diameter \( \sim 300 \mu m \). The resolution improves for solid PMMA resonators, and using hollow PMMA spheres, the value of \( \sim 10^{-6} \) N was demonstrated. The dynamic measurement range of the sensors are determined by the elastic deformation limit of the material. It is shown that the sensitivity is solely defined by the size of the sphere for a given material. Once the universal calibration curve is obtained for a given sphere material, the only variable that determines the “gain” of the instrument is the sphere size.

This research was supported by the National Science Foundation through grants IIP-0539067 and CBET-0619193.

References