ABSTRACT: The detection of electric field by monitoring the optical whispering gallery mode shifts of polymeric microspheres is demonstrated. Two types of spheres are considered; (i) a polydimethylsiloxane (PDMS) sphere with 60 parts base silicon elastomer-to-1 part polymer curing agent by volume and; (ii) a silica sphere coated with a PDMS (uncured) base. The optical mode shifts are caused by perturbations to the resonator morphology induced by electrostriction effect in the presence of an external electric field. Preliminary experiments show that the latter microsphere yields higher sensitivity (0.027 pm/V m$^{-1}$) with a measurement precision of $\sim$1.8 V/m. 

KEYWORDS: composites; elastomers; electrostriction; fibers; microsphere; morphology dependent resonances (MDR); polydimethylsiloxane (PDMS); polymeric photonic sensor; refractive index; whispering gallery optical modes (WGM)

INTRODUCTION High optical quality factor ($Q$) dielectric microspheres have received significant attention in recent years for their potential application in a range of fields including spectroscopy and microcavity laser technology. Sensors exploiting the whispering gallery mode (WGM) shifts of microspheres have also been proposed for biological applications, trace gas detection, impurity detection in liquids, as well as mechanical sensing including force, pressure, temperature, and wall shear stress for aerodynamic applications.

In recent years, electrically tunable liquid crystal-based optical microresonators have also been investigated with the main focus of achieving the maximum possible tuning range. In one study, a maximum tuning of 0.2 nm was achieved by applying an electric field of 200 kV/m to a microring resonator with a nematic liquid crystal (NLC) as the cladding layer. In a similar arrangement, using a microdisk in place of the microring, an irreversible WGM shift of 6 nm was achieved with an electric field of 30 kV/m. In another study, using a lithium niobate microring resonator a 0.4 nm WGM shift was obtained in an electric field of 1.5 MV/m.

The largest WGM shift of 20 nm was obtained using a liquid crystal microsphere. The corresponding electric field for this case was 2.6 MV/m. Assuming linear response, the tuning sensitivity in these studies was limited to the range between 0.001 pm/V m$^{-1}$ and 0.2 pm/V m$^{-1}$. The latter is obtained in the irreversible tuning arrangement by Piegdon et al.

Further, in these studies the microcavity $Q$-factors were between 10$^3$ and 10$^4$, also limiting the tuning resolution.

Recently, homogenous polymeric microspheres were used as electric-field induced optical tuners. A 600-μm diameter 60:1 base-to-curing agent ratio polydimethylsiloxane (PDMS) was subjected to a uniform external electric field. It was observed that the electric field sensitivity was a function of poling duration prior to testing. After 6 hours of poling in an external electric field of $\sim$100 kV/m, an electric field sensitivity of 0.2 pm/kV m$^{-1}$ was obtained.

The observed optical mode shifts are caused by the deformation of the elastic sphere under electric field. This effect is commonly called “electrostriction.” Under an external electric field, the sphere tends to elongate in the field direction caused by both body and surface forces acting on the sphere. The body forces are induced by the gradients in both the electric field and electric permeability distribution in the sphere. The surface force (electrostatic force) acts at the interface between the sphere and the surrounding medium. The perturbation of the sphere’s morphology leads to a shift in its WGM.

The objective of the present study is to further explore the use of the electrostriction effect in polymer spheres to monitor electric field. In addition to the homogeneous 60:1 base-to-curing agent ratio PDMS sphere mentioned above, a
composite sphere with a silica core and a PDMS base outer layer is also investigated.

EXPERIMENTAL

Microsphere Fabrication

The ~600-μm diameter homogeneous PDMS sphere is fabricated as follows. First, the PDMS base (Sylgard 184 by Dow Corning) is mixed with the curing agent (60:1 ratio by volume). We use this ratio instead of the standard 10:1 in order to lower the Young’s modulus of the elastomer and increase the electrostriction effect. Next, a 125-μm diameter silica fiber is dipped into the mixture to form a sphere at the fiber’s tip and then cured for 4 hours at a temperature of 100 °C to form a soft, pliable solid sphere [Fig. 1(a, c)].

The ~500-μm diameter silica inner layer of the composite sphere is prepared by melting the tip of a single mode optical fiber using a microtorch. Then this silica microsphere is coated with a ~150-μm thick outer layer by dipping it in PDMS base. Note that no curing agent is used on the PDMS base. Thus, the outer layer remains as a high-viscosity yield-stress (Bingham) liquid [Fig. 1(b, d)]. The coat is thin enough so that the yield stress of the fluid and the surface tension overcome the body force and the liquid does not flow.

Opto-Electronic Setup

A tunable diode laser with central frequency of 1.312 μm is used to interrogate the optical modes (WGM) of the microspheres. The laser light is coupled to a single mode optical fiber. As in our previous micro-optical sensor studies, a section of the optical fiber is tapered to evanescently couple the laser light into the composite sphere. In the case of the composite sphere, the light travels only in the PDMS outer shell and monitors the changes in the morphology of this outer layer induced by the electric field. The transmission spectrum through the fiber is monitored by a photodiode whose output is digitized using a 16 bit analog-to-digital converter and analyzed on a personal computer to determine the WGM shift. The microsphere sensor is placed between two parallel brass plates as shown in Figure 2. The uniform electric field is obtained by applying voltage to the plates through a function generator. Experiments were carried out at constant temperature to avoid temperature-induced WGM shifts caused by thermal expansion and thermo-optic effects.9–11

Before each experiment the spheres are poled for 3 hours in uniform external electric field of 1 MV/m and 50 kV/m for the homogeneous and composite spheres, respectively. The poling partially polarizes the polymer increasing the electrostriction effect (as observed in ref. 17). A representative experimental result for the composite sphere is shown in Figure 3 where the transmission spectra with and without the external electric field are plotted. Note that the polarization of an optical mode in the sphere is predominantly in a plane orthogonal to the light propagation and the observed resonances can be transverse electric (TE) or transverse magnetic (TM) modes. For large circumferential mode numbers (l = λ/2π r n ≫ 1, where r and n are the sphere radius and refractive index), the effect of mode polarization is negligible.6 The optical Q-factor for the resonance shown in this figure is ~3 × 10^5. The figure indicates that a WGM shift of 8 pm is induced by a 290 V/m electric field.

FIGURE 1 Photograph (a and b) and schematic of the of homogeneous and composite sphere (c and d), respectively.

FIGURE 2 Photograph of homogeneous sphere with plate electrodes.

FIGURE 3 Transmission spectra through the sphere-coupled fiber.

Electrodes

Micro-sphere
RESULTS AND DISCUSSION

Both the homogeneous and the composite spheres were placed between electrodes (Fig. 2) and subjected to harmonic external electric field by supplying voltage to the plates from a function generator. Figure 4 shows the WGM shifts of the homogeneous sphere under 1 Hz harmonic electric field. The 180° phase between the electric field and the WGM shift indicates that under positive electric field (in the direction of poling), the sphere elongates leading to a blue shift in $d\lambda$. Conversely, when the field is negative, the sphere is compressed at the poles leading to a red shift in $d\lambda$. The corresponding sensitivity plot is presented in Figure 5. The solid line is the best fit of the data using least squares method and indicates a sensitivity of $\frac{d\lambda}{dE} = 0.0017 \text{ pm/V m}^{-1}$. The standard deviation of the data in this case was $d\lambda = 0.34 \text{ pm}$. The results indicate an electric field resolution of $\frac{dE}{d\lambda} \approx 200 \text{ V/m}$ for the homogeneous sphere sensor.

Figure 6 shows the WGM shift of the composite sphere under a 0.2 Hz harmonic electric field perturbation with 10V/m amplitude. The result is similar to that of the homogeneous sphere and the composite sphere tracks the harmonic modulation in the electric field well. The corresponding sensitivity plot of WGM shift vs. electric field is presented in Figure 7. The best fit of the data (solid line) indicates a sensitivity of $\frac{d\lambda}{dE} = 0.027 \text{ pm/V m}^{-1}$. The corresponding electric field resolution is $\frac{dE}{d\lambda} \approx 1.8 \text{ V/m}$. 

![Figure 4](image1.png)

**FIGURE 4** WGM shift of the homogeneous 60:1 PDMS microsphere under harmonic external electric field.

![Figure 5](image2.png)

**FIGURE 5** Electric field sensitivity for the homogeneous PDMS microsphere of Figure 4.

![Figure 6](image3.png)

**FIGURE 6** WGM shift of the composite sphere under harmonic field perturbation.

![Figure 7](image4.png)

**FIGURE 7** Electric field sensitivity for the composite microsphere of Figure 6.

![Figure 8](image5.png)

**FIGURE 8** Sensitivity of homogeneous sphere as a function of harmonic electric field.
In this case, the standard deviation of the data scatter was $\delta \lambda = 0.05$ pm.

The above experiments show promising electric field sensitivities. However, these measurements were made at low frequencies (0.2 and 1 Hz) of electric field modulations. The dependence of measurement sensitivity on electric field modulation frequency is investigated next. Figures 8 and 9 show the frequency dependence of the electric field sensitivity, $d\lambda/dE$. In these experiments, the electric field amplitude is kept constant (2000 V/m and 10 V/m, respectively, for the homogeneous and the composite spheres) as the frequency is varied. These figures show that both spheres are mechanically over-damped and the sensitivities rapidly drop with increasing frequency. The frequency damping is more severe for the composite sphere. By using harder elastomers (e.g., lower base-to-curing agent ratio mixtures), the mechanical overdamping may be avoided. However, this will cause a reduction in electric field sensitivity.

CONCLUSIONS

The results show that polymeric microspheres can be used for high-resolution detection of electric field. The silica-PDMS composite sphere provides higher resolution ($\sim 1.85$ V/m) compared with the homogeneous 60:1 PDMS sphere ($\sim 200$ V/m). However, both spheres are mechanically over-damped and the sensitivity drops with increasing field frequency. This limits their applicability to transient electric field detection at high frequencies. Future work will focus on the investigation of several new polymers and composite sphere geometries to improve mechanical bandwidth while maintaining sensitivity.

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REFERENCES AND NOTES