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Fiber Optic Excitation of Silicon Microspheres in Amorphous and Crystalline Fluids

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ABSTRACT
This study investigates the optical resonance spectra of free-standing monolithic single crystal silicon microspheres immersed in various amorphous fluids, such as air, water, ethylene glycol, and 4-Cyano-4'-pentylibiphenyl nematic liquid crystal. For the various amorphous fluids, morphology-dependent resonances with quality factors on the order of $10^5$ are observed at 1428 nm. The mode spacing is always on the order of 0.23 nm. The immersion in various amorphous fluids affects the spectral response of the silicon microsphere and heralds this technique for use in novel optofluidics applications. Even though the nematic liquid crystal is a highly birefringent, scattering, and high-index optical medium, morphology-dependent resonances with quality factors on the order of $10^5$ are observed at 1300 nm in the elastic scattering spectra of the silicon microsphere, realizing a liquid-crystal-on-silicon geometry. The relative refractive index and the size parameter of the silicon microsphere are the parameters that affect the resonance structure. The more 4-Cyano-4'-pentylibiphenyl interacting with the silicon microsphere, the lower the quality factor of the resonances is. The more 4-Cyano-4'-pentylibiphenyl is interacting with the silicon microsphere, the lower the mode spacing $\Delta \lambda$ of the resonances is. The silicon microspheres wetted with nematic liquid crystal can be used for optically addressed liquid-crystal-on-silicon displays, light valve applications, or reconfigurable optical networks.

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1. Introduction
Optical microcavities are interesting structures for their high-quality factor resonances and small mode volumes. Micro-ring [1] resonators and microspheres [2] are the most common optical microcavities [3]. On the topological side, microspheres [3] are the 3D analogue of 1D Fabry–Pérot [4] resonators. Light scattering from single and ensembled [5] microspheres finds applications in optics [6]. Glass microspheres are being used for frequency conversion [7], optical channel dropping [8], and sensing [9]. In particular, optical fibers coupling to optical microspheres opened up a new field of evanescent wave optical sensors [10]. Spherical microcavities are sensitive to tiny alterations and...
modifications in the vicinity of the outer wall surfaces [11]. Microspheres are also integrable into microfluidic lab-on-chip systems [12].

Microfluidics [13], as a highly developing field, found many applications in optics, thereby leading to the establishment of optofluidics [14]. Optofluidics, which is the combination of light and non-solids, offer very interesting applications in fields ranging from interferometry [15], imaging [16], detection of chemical or biological agents [17], and particle control [18] to enhancing photonic circuits and energy generation [19]. Optofluidics brings together light and liquids to provide such technologies as fluid waveguides [20], deformable lenses [21], and microdroplet lasers [22]. Optical lab-on-chip development aims to continue to reduce device size and cost and improve the sensitivity [23].

Optofluidics offers fluidic and optical advantages over more conventional bulk liquid analytic chemical and biomedical diagnostic techniques, such as flow cytometry and liquid chromatography. For example, immiscible fluid–fluid interfaces are smooth [24]. Also, diffusion can create a controllable blend of optical properties [25]. Additionally, fluid can be an excellent transport medium [26]. The optical advantages of the optofluidics include the availability of numerous high sensitivity optical sensing techniques [27], the occurrence of localized light at biological scales [28], and the possibility of light to manipulate fluids and objects suspended in fluids [29]. The confinement of laser light in solid core waveguides using the total internal reflection (TIR) confinement mechanism is replicated in optofluidic waveguides [30]. Many researchers have characterized liquid-core/solid-cladding and solid-core/liquid-cladding waveguides because of their reconfiguration [31]. Optical transport and trapping based on the evanescent field using photonic structures has several advantages over free-space systems [32]. Planar photonic structures used in microfluidic devices eliminate the need for table-top free-space optics, reducing the costs and increasing the platform portability [33].

Silicon is a promising material for microfluidic channels on lab-on-a-chip for label-free, optical biochemical sensing applications of near-infrared (IR) wavelengths [34]. The lab-on-a-chip silicon optofluidic sensors can be physically compact due to the high refractive index contrast between the silicon and fluid and economic due to the complementary metal-oxide semiconductor (CMOS) compatible production [35]. A hybrid silicon–polydimethylsiloxane (PDMS) optofluidic platform has been proposed for sensing applications [36], and silicon ring antiresonant reflecting optical waveguides (ARROWs) have been used in optofluidics [37].

Moreover, liquid crystal (LC) technology [38], especially LC-on-silicon (LCOS) technology [39], have been used in information displays, sensors, bio- and medical molecular devices, and smart materials for new energy applications due to their unique electro-optic properties [40]. Specifically, LCs are being used as optical filters and switches, beam-steering devices, spatial light modulators, integrated devices based on optical waveguiding, lasers, and optical nonlinear components [41]. The fundamental light modulation mechanism of an LC display (LCD) is electric field-induced molecular reorientation, which, in turn, causes refractive index change. Moreover, LCs are photostable in the ultraviolet (UV) [42] and long wavelength IR range [43], which improves the lifetime of LCD devices. The refractive indices of an LC are mainly determined by the molecular structure, wavelength, and operating temperature [44]. Optical, dielectric, and elastic anisotropies are exhibited in an aligned LC. In a homogeneous cell, the refractive index
of the LC depends on the direction of the incident linearly polarized light. If the incident linearly polarized light is parallel to the LC director, the corresponding refractive index is extraordinary $N_e$, and if the incident linearly polarized light is perpendicular to the LC director, the corresponding refractive index is ordinary $N_o$. Most LC compounds and mixtures possess a positive birefringence $N_e - N_o > 0$, i.e., $N_e > N_o$.

Silicon, therefore a promising material for microphotonics [34], such as light emission, amplification, waveguiding, modulation, and detection [45], can find applications in optofluidics and LCOS. Silicon microspheres have already been used in channel dropping [46] and considered for optoelectronic applications [47]. Silicon microspheres have been used for optical modulation applications in air [48] and in nematic LCs (NLCs) [49]. Recently, silicon microspheres have been used for polarization studies [50] as well as optical spectroscopy [51]. Germanium microspheres [52] were also studied for electronic and photonic integration applications.

This article reports, for the first time to the best knowledge of the authors, the observation of optical resonances from free-standing monolithic single crystal silicon microspheres immersed in various amorphous fluids, such as air, water, ethylene glycol, and NLC placed on a silica optical fiber half-coupler (OFHC) and excited with a tunable near-IR laser. The immersion in various fluids affects the spectral response of the silicon microsphere and heralds this technique for use in novel optofluidics applications. In addition, this technique can be used in novel optically addressed LCOS displays, light valves, or reconfigurable optical networks.

2. Morphology-dependent resonances (MDRs)

Optical resonances in a spherical cavity are explained in Lorenz–Mie theory [53, 54]. When the optical path inside a cavity is equal to an integer multiple of wavelength, a standing wave occurs in the cavity. For large microspheres ($a \gg \lambda$), with refractive index $N_1$ and radius $a$, the condition for the standing wave to occur is

\[ \frac{\lambda}{N_1} \approx 2\pi a, \]  

where $\lambda/N_1$ is the wavelength of light in the microsphere, and $n$ is an integer. Frequently, a dimensionless size parameter is defined to be used in expressions of this system:

\[ x = \frac{2\pi Na}{\lambda}, \]  

where $N$ is the refractive index of the medium. The standing-wave condition can then be expressed as a function of the size parameter, integer multiple, and the relative refractive index $M = N_1/N$, such as

\[ x \approx \frac{nN}{N_1} = \frac{n}{M}, \]  

where $n$ is the angular momentum quantum number.

Equation (3) shows that the standing wave or so-called MDRs are dependent on angular momentum quantum number $n$, on radius of the microsphere $a$, and the refractive index of medium $N$ and microsphere $N_1$. When light is considered as an
electromagnetic wave, resonances are defined by polar angular \((n)\) and radial \((l)\) and azimuthal angular \((m)\) mode numbers. The resonance structure of microspheres is explained by the mode spacing, which is the spectral distance between two consecutive polar angular \((n)\) modes having the same radial mode number \((l)\) \[55\]:

\[
\Delta \lambda = \frac{\lambda^2 \arctan \left( \frac{M^2 - 1}{2C_0} \right)}{2\pi a N (M^2 - 1)^{1/2}}.
\] (4)

3. Silicon microspheres in amorphous liquids

Figure 1 shows the experimental setup used for elastic scattering from a silicon microsphere with radius \(a = 500 \, \mu\text{m}\) and refractive index \(N_1 = 3.5\). A near-IR tunable distributed feedback (DFB) laser with wavelength of \(\lambda = 1428\, \text{nm}\) is coupled to a single-mode OFHC. The silicon microsphere is placed on the OFHC, and light is evanescently coupled from the OFHC to the silicon microsphere. The 90° elastic scattering from the silicon microsphere is observed with a microscope equipped with an indium gallium arsenide (InGaAs) photodiode. A beam splitter is used in the microscope to image and position the microsphere to an optimal position of the OFHC for sufficient light coupling. The 0° transmission through the OFHC is also observed with an InGaAs photodiode.

Figure 2 shows the 0° transmission and 90° elastic scattering spectra for a silicon microsphere placed on the OFHC in air. The measured mode spacing \(\Delta \lambda = 0.23\, \text{nm}\) compares favorably with the estimated value. Observation of MDRs in aqueous solutions is important for biochemical sensing applications, since sensing experiments are mostly performed in aqueous solutions.

Due to the high refractive index \((N_1 = 3.5)\) and large radius \((a = 500 \, \mu\text{m})\) of the silicon microspheres, MDRs are narrow in linewidth and dense in the scattering and transmission spectra. The highest \(Q\)-factors measured are around \(10^5\), which are limited by the linewidth of the DFB diode laser. With unpolarized input laser light, both the transverse electric (TE) and the transverse magnetic (TM) MDRs are excited, resulting in rich scattering spectra. However, since the observation of the MDRs is instrument limited, all of the available MDRs (with TE and TM polarizations) are not observed \[31\].

![Figure 1. Schematic of the experimental setup for silicon microspheres in amorphous liquids.](image-url)
Observation of resonances with different mode numbers is instrument limited because of the excessive number of radial and polar modes with both TE and TM polarizations. Hence, the measured resonances are actually a collection of resonances with different radial mode numbers and the number of resonances in one mode spacing distance is related to the resolution of the measurement. MDRs are observed as peaks in the 90° elastic scattering and dips in the 0° transmission spectra.

Figure 3 shows the 0° transmission and the 90° elastic scattering spectra for a silicon microsphere placed on the OFHC in water. Since the refractive index of water is $N = 1.32$, the background of the 90° elastic scattering signal increased and the background of the 0° transmission signal decreased with respect to those in air. Ideally, water is a homogeneous medium; however, in aqueous solutions, the contaminants have to be taken into account.

Figure 2. 90° elastic scattering and 0° transmission spectra of the silicon microsphere in air.

Figure 3. 90° elastic scattering and 0° transmission spectra of the silicon microsphere in water.
consideration, and the relatively low Q-factors of MDRs in water can be attributed to the losses due to the scattering of the particles staying on the surface of the silicon microsphere. The measured mode spacing $\Delta \lambda = 0.23$ nm compares favorably the estimated value.

Figure 4 shows the $0^\circ$ transmission and $90^\circ$ scattered spectra for a silicon microsphere placed on the OFHC in ethylene glycol, which is a pure, colorless organic molecule with a refractive index of $N = 1.41$. Even though the background signal increases in $90^\circ$ elastic scattering and decreases in the $0^\circ$ transmission, the pure and homogeneous structure of the ethylene glycol molecule leads to high Q-factor measurements of the MDRs of the silicon microsphere. The Q-factors in ethylene glycol medium are even comparable to or better than the Q-factors in air. The reason for this enhancement of the Q-factor may be due to the treatment of the silicon surface by the adsorption of ethylene glycol [56]. The measured mode spacing $\Delta \lambda = 0.23$ nm compares favorably with the estimated value.

4. Silicon microspheres in LC

A near-IR tunable DFB laser with wavelength of $\lambda = 1302$ nm is coupled to the OFHC. NLCs, such as 4-Cyano-4'-pentylbiphenyl (5CB), provide the possibility to change the surroundings of the silicon microsphere. A glass slide is used to precisely control the position of the silicon microsphere. 5CB only interacts with the silicon microsphere from the top. The high scattering orientation of 5CB easily degrades the MDRs of the silicon microsphere. Even small amounts of 5CB can result in large scattering. Figure 5 shows the experimental setup schematic for the silicon sphere in NLC.

Figure 6 shows two micrographs of a silicon microsphere suspended by the surface tension from two different 5CB amounts. In Figure 6, the OFHC is detached from the silicon microsphere for clarity. These micrographs of Figure 6 correspond to the two spectra in Figure 7. Note that a very small amount of 5CB is interacting with the microsphere. The Q-factor of the resonances is $Q = 3.09 \times 10^5$ for excess and $Q = 4.19 \times 10^5$ for...
a small amount of 5 CB NLC. The more 5CB interacting with the silicon microsphere, the lower the Q-factor of the resonances is. This effect is very well demonstrated in Figure 7. The more 5CB interacting with the silicon microsphere, the lower the mode spacing $\Delta \lambda$ of the resonances is. This effect is very well demonstrated in Figure 6 as well. The mode spacing $\Delta \lambda = 0.16$ nm for excess and $\Delta \lambda = 0.2$ nm for a small amount of 5 CB NLC.

5. Conclusions

This article has demonstrated the observation of optical resonances from free-standing monolithic single crystal silicon microspheres in different amorphous fluids, such as air, water, and ethylene glycol. The observation of optical resonances from free-standing monolithic single crystal silicon microspheres immersed in various amorphous fluids (e.g., air, water, and ethylene glycol) is believed to open up a variety of possibilities for lab-on-a-chip optofluidic applications of silicon microsphere photonics.

In addition, the dependence is reported for the optical resonance spectra of a silicon microsphere wetted with various amounts of NLC placed on a silica OFHC and excited with a tunable near-IR laser. The more 5CB interacting with the silicon microsphere, the lower the Q-factor of the resonances is. The more 5CB interacting with the silicon microsphere, the lower the mode spacing $\Delta \lambda$ of the resonances is. This configuration of
silicon microsphere in an NLC can be used in novel optically addressed LCOS displays, light valves, or reconfigurable optical networks.

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**Figure 7.** 0° transmission from silicon sphere: (a) wetted with excess 5CB NLC and (b) wetted with a small amount of 5CB NLC.
References


**Biographies**

Huzeyfe Yılmaz received his B.Sc. degree in Physics from Bilkent University in 2009. He received his M.Sc. degree in Physics in 2011 from Koç University, where he worked on “Elastic Light Scattering from Glass and Silicon Microspheres in Organic and Crystalline Liquids and in Aqueous Solutions” with Prof. Ali Serpengüzel at the Microphotonics Research Laboratory. Currently, he is a Ph.D. student with Prof. Lan Yang at Washington University Micro/Nano Photonics Laboratory in St. Louis, Missouri, USA.

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