

Fiber Optic Excitation of Silicon Microspheres in Amorphous and Crystalline Fluids

Huzyefe Yilmaz, Hasan Yilmaz, Mohammed Sharif Murib & Ali Serpengüzel

To cite this article: Huzyefe Yilmaz, Hasan Yilmaz, Mohammed Sharif Murib & Ali Serpengüzel (2016) Fiber Optic Excitation of Silicon Microspheres in Amorphous and Crystalline Fluids, Fiber and Integrated Optics, 35:2, 60-71, DOI: [10.1080/01468030.2015.1138005](https://doi.org/10.1080/01468030.2015.1138005)

To link to this article: <https://doi.org/10.1080/01468030.2015.1138005>



Published online: 18 Apr 2016.



Submit your article to this journal [↗](#)



Article views: 152



View related articles [↗](#)



View Crossmark data [↗](#)

Fiber Optic Excitation of Silicon Microspheres in Amorphous and Crystalline Fluids

Huzeyfe Yılmaz^{a,b}, Hasan Yılmaz^{a,c}, Mohammed Sharif Murib^{a,d} and Ali Serpengüzel^a

^aDepartment of Physics, Microphotonics Research Laboratory, Koç University, Istanbul, Turkey; ^bDepartment of Electrical and Systems Engineering, University of Washington, St. Louis, MO, USA; ^cComplex Photonic Systems (COPS) Chair Group, MESA+ Institute for Nanotechnology, University of Twente, Enschede, Netherlands; ^dCollege of Engineering and Technology, American University of the Middle East, Dasman, Kuwait

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'-pentylbiphenyl 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'-pentylbiphenyl interacting with the silicon microsphere, the lower the quality factor of the resonances is. The more 4-Cyano-4'-pentylbiphenyl 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.

ARTICLE HISTORY

Received 24 November 2015
Accepted 30 December 2015

KEYWORDS

Liquid crystal on silicon; optical microcavity; optical resonator; silicon microsphere; silicon photonics

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

CONTACT Ali Serpengüzel  aserpenguzel@ku.edu.tr  Department of Physics, Microphotonics Research Laboratory, Koç University, Rumelifeneri Yolu, Sarıyer, Istanbul, 34450, Turkey.

© 2016 Taylor & Francis

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 flexibility in the 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

$$n \frac{\lambda}{N_1} \approx 2\pi a, \quad (1)$$

where λ/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:

$$x \approx \frac{2\pi Na}{\lambda}, \quad (2)$$

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

$$x \approx \frac{nN}{N_1} = \frac{n}{M}, \quad (3)$$

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]:

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

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].

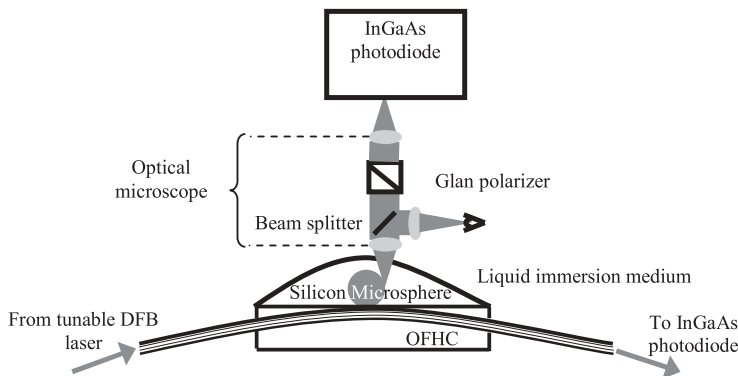


Figure 1. Schematic of the experimental setup for silicon microspheres in amorphous liquids.

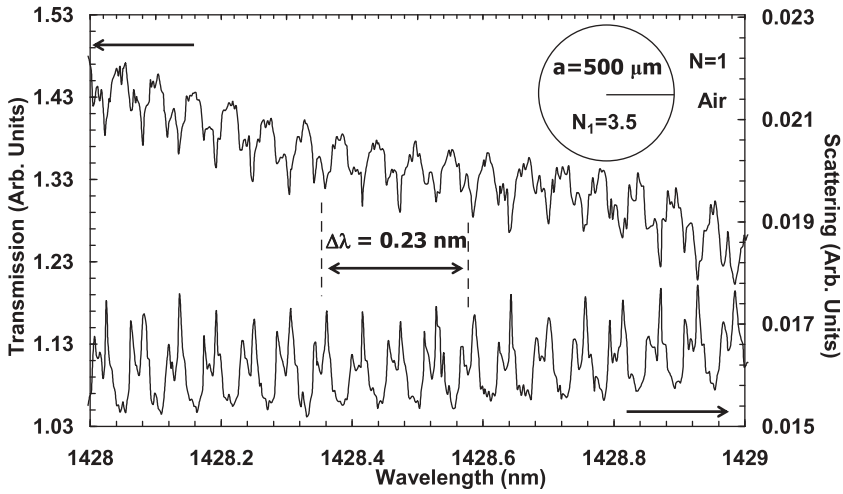


Figure 2. 90° elastic scattering and 0° transmission spectra of the silicon microsphere in air.

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

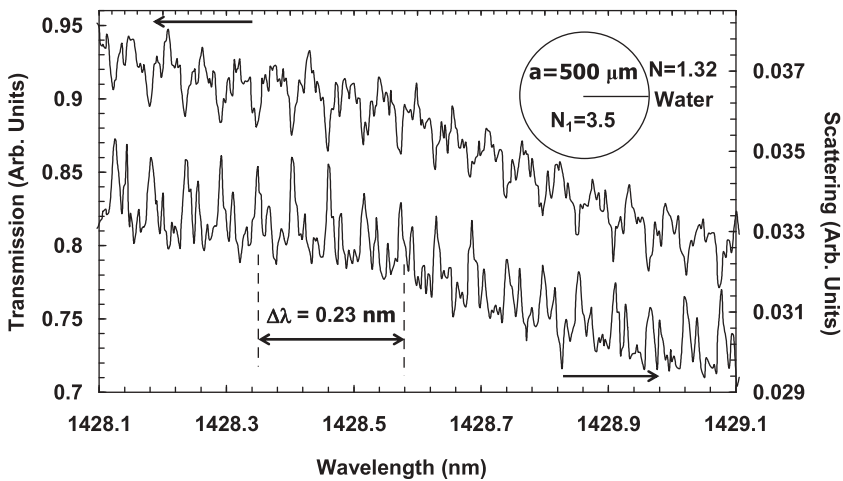


Figure 3. 90° elastic scattering and 0° transmission spectra of the silicon microsphere in water.

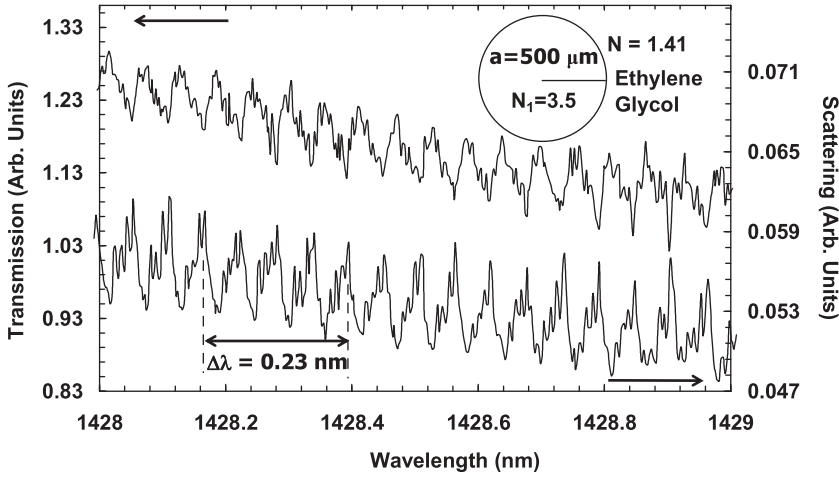


Figure 4. 90° elastic scattering and 0° transmission spectra of the silicon sphere in ethylene glycol.

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° transmission and 90° 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° elastic scattering and decreases in the 0° 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

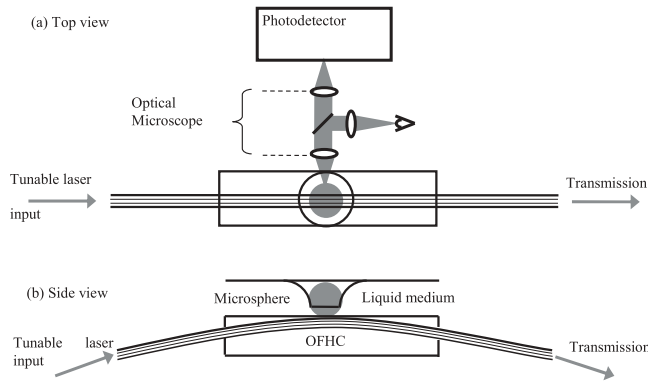


Figure 5. Experimental setup schematic for silicon sphere in NLC: (a) top view and (b) side view.

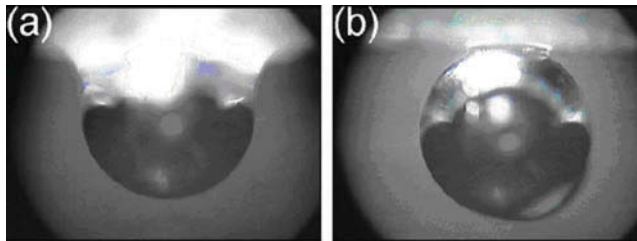


Figure 6. Micrographs of silicon microsphere: (a) wetted with excess 5CB and (b) wetted with a small amount of 5CB.

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

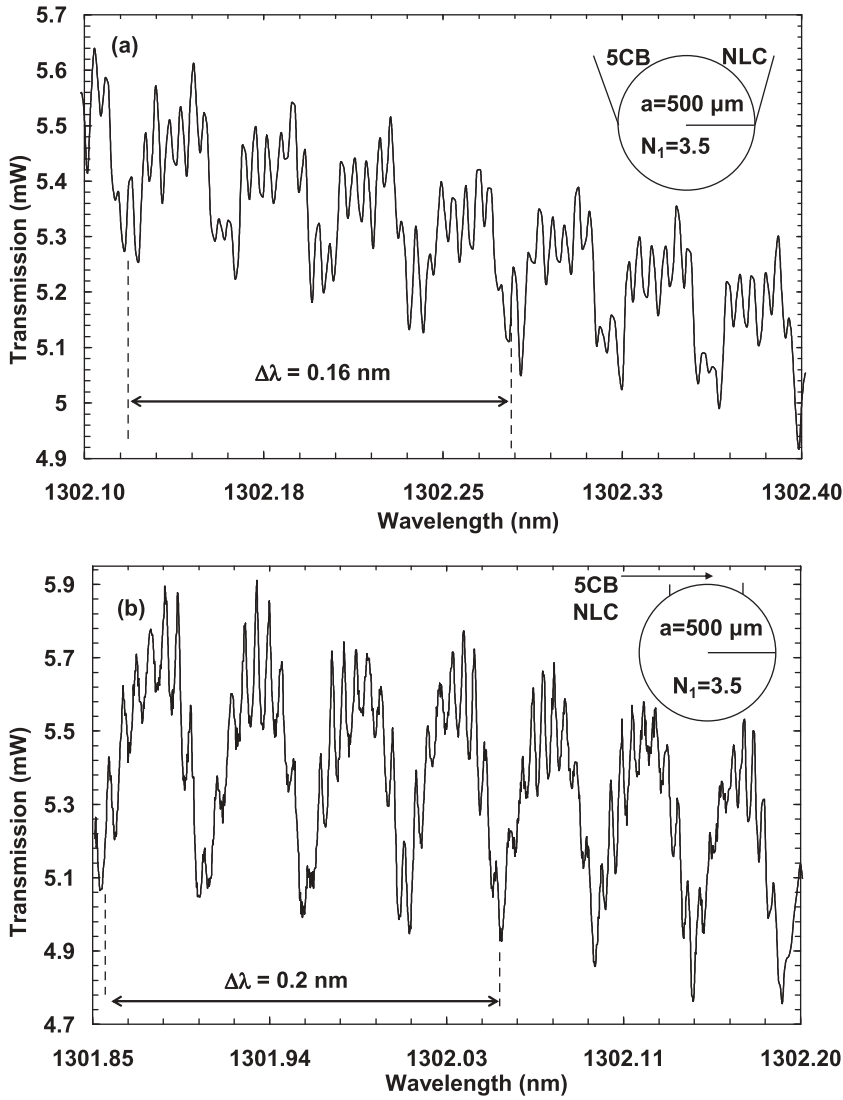


Figure 7. 0° transmission from silicon sphere: (a) wetted with excess 5CB NLC and (b) wetted with a small amount of 5CB NLC.

silicon microsphere in an NLC can be used in novel optically addressed LCOS displays, light valves, or reconfigurable optical networks.

Funding

The authors would like to acknowledge the partial support of this research by the Scientific and Technological Research Council of Turkey (TUBITAK; grant EEEAG-106E215) and the European Commission (EC; grants FP6-IST-003887 NEMO and FP6-IST-511616 PHOREMOST).

References

1. Little, B. E., Chu, S. T., Haus, H. A., Foresi, J., and Laine, J. P. 1997. Microring resonator channel dropping filters. *Journal of Lightwave Technology* 15:998–1005.
2. Benner, R. E., Barber, P. W., Owen, J. F., and Chang, R. K. 1980. Observation of structure resonances in the fluorescence spectra from microspheres. *Physical Review Letters* 44:475–478.
3. Serpengüzel, A., and Poon, A. W., Eds. 2011. *Optical Processes in Microparticles and Nanostructures: A Festschrift Dedicated to Richard Kounai Chang on His Retirement from Yale University*. Singapore: World Scientific Press.
4. Fabry, C., and Pérot, A. 1899. Théorie et applications d'une nouvelle méthode de spectroscopie interférentielle. *Annales de Chimie et de Physique* 16:115–144.
5. Vázquez-Estrada, O., and García-Valenzuela, A. 2014. Optical reflectivity of a disordered monolayer of highly scattering particles: coherent scattering model versus experiment. *Journal of the Optical Society of America A* 31:745–754.
6. Barber, P. W., and Chang R. K., Eds., 1988. *Optical Effects Associated with Small Particles*. Singapore: World Scientific Press.
7. Farnesi, D., Barucci, A., Righini, G. C., Berneschi, S., Soria, S., and Nunzi Conti, G. 2014. Optical frequency conversion in silica-whispering-gallery-mode microspherical resonators. *Physical Review Letters* 112:093901-1–093901-5.
8. Bilici, T., Işçi, S., Kurt, A., and Serpengüzel, A. 2004. Microsphere-based channel dropping filter with an integrated photodetector. *IEEE Photonics Technology Letters* 16:476–478.
9. Vollmer, F., and Arnold, S. 2008. Whispering-gallery-mode biosensing: label-free detection down to single molecules. *Nature Methods* 5:591–596.
10. Serpengüzel, A., Arnold, S., and Griffel, G. 1995. Excitation of resonances of microspheres on an optical fiber. *Optics Letters* 20:654–656.
11. Wu, Y., Zhang, D. Y., Yin, P., and Vollmer, F. 2014. Ultraspecific and highly sensitive nucleic acid detection by integrating a DNA Catalytic network with a label-free microcavity. *Small* 10:2067–2076.
12. Nitkowski, A., Gondarenko, A., and Lipson, M. 2010. On-chip supercontinuum optical trapping and resonance excitation of microspheres. *Optics Letters* 35:1626–1628.
13. Whitesides, G. M. 2006. The origins and the future of microfluidics. *Nature* 442:368–373.
14. Chen, Y.-F., Jiang, L., Mancuso, M., Jain, A., Oncescu, V., and Erickson, D. 2012. Optofluidic opportunities in global health, food, water and energy. *Nanoscale* 4:4839.
15. Schimpf, A., Bucci, D., Nannini, M., Magnaldo, A., Couston, L., and Broquin, J.-E. 2012. Photothermal microfluidic sensor based on an integrated Young interferometer made by ion exchange in glass. *Sensors and Actuators B: Chemicals* 163:29–37.
16. Vasdekis, A. E., and Laporte, G. P. 2011. Enhancing single molecule imaging in optofluidics and microfluidics. *International Journal of Molecular Science* 12:5135–5156.
17. Fan, X., and White, I. M. 2011. Optofluidic microsystems for chemical and biological analysis. *Nature Photonics* 5:591–597.
18. Kayani, A. A., Khoshmanesh, K., Ward, S. A., Mitchell, A., and Kalantar-Zadeh, K. 2012. Optofluidics incorporating actively controlled micro- and nano-particles. *Biomicrofluidics* 6:031501-01–031501-32.
19. Erickson, D., Sinton, D., and Psaltis, D. 2011. Optofluidics for energy applications. *Nature Photonics* 5:583–590.
20. Wolfe, D. B., Conroy, R. S., Garstecki, P., Mayers, B. T., Fischbach, M. A., Paul, K. E., Prentiss, M., and Whitesides, G. M. 2004. Dynamic control of liquid-core/liquid-cladding optical waveguides. *Proceedings of the National Academy Sciences* 101:12434–12438.
21. Fei, P., He, Z., Zheng, C., Chen, T., Men, Y., and Huang, Y. 2011. Discretely tunable optofluidic compound microlenses. *Lab Chip* 11:2835–2841.
22. Fan, X., and Yun, S.-H. 2014. The potential of optofluidic biolasers. *Nature Methods* 11:141–147.

23. Soria, S., Berneschi, S., Brenci, M., Cosi, F., Conti, G. N., Pelli, S., and Righini, G. C. 2011. Optical microspherical resonators for biomedical sensing. *Sensors* 11:785–805.
24. Zhao, B., MacMinn, C. W., Szulczewski, M. L., Neufeld, J. A., Huppert, H. E., and Juanes, R. 2013. Interface pinning of immiscible gravity-exchange flows in porous media. *Physical Review E* 87:023015-1–023015-7.
25. Monat, C., Domachuk, P., and Eggleton, B. J. 2007. Integrated optofluidics: A new river of light. *Nature Photonics* 1:106–114.
26. Psaltis, D., Quake, S. R., and Yang, C. 2006. Review article developing optofluidic technology through the fusion of microfluidics and optics. *Nature* 442:381–386.
27. Mandal, S., and Erickson, D. 2008. Nanoscale optofluidic sensor arrays. *Optics Express* 16:1623–1631.
28. Hunt, H. K., and Armani, A. M. 2010. Label-free biological and chemical sensors. *Nanoscale* 2:1544–1559.
29. Psaltis, D. 2006. Optofluidics. In *Proceedings of the IEEE/LEOS International Conference on Optical MEMS and Their Applications*, p174. Piscataway Township, NJ: IEEE.
30. Cho, S. H., Godin, J. M., Chen, C.-H., Qiao, W., Lee, H., and Lo, Y.-H. 2010. Review article: Recent advancements in optofluidic flow cytometer. *Biomicrofluidics* 4:043001-1–043001-23.
31. Chung, A. J., and Erickson, D. 2011. Optofluidic waveguides for reconfigurable photonic systems. *Optics Express* 19:8602–8609.
32. Schmidt, B. S., Yang, A. H. J., Erickson, D., and Lipson, M. 2007. Optofluidic trapping and transport on solid core waveguides within a microfluidic device. *Optics Express* 15:14322–14334.
33. Zhang, D., Men, L., and Chen, Q. 2011. Microfabrication and applications of opto-microfluidic sensors. *Sensors* 11:5360–5382.
34. Soref, R. 2006. The past, present, and future of silicon photonics. *IEEE Journal of Selected Topics in Quantum Electronics* 12:1678–1687.
35. Wang, J., Yao, Z., and Poon, A. W. 2015. Silicon-nitride-based integrated optofluidic biochemical sensors using a coupled-resonator optical waveguide. *Frontiers in Materials* 2:1–13.
36. Testa, G., Persichetti, G., Sarro, P. M., and Bernini, R. 2014. A hybrid silicon-PDMS optofluidic platform for sensing applications. *Biomedical Optics Express* 5(2):417–426.
37. Testa, G., Huang, Y., Sarro, P. M., Zeni, L., and Bernini, R. 2010. Integrated silicon optofluidic ring resonator. *Applied Physics Letters* 97:131110-1–131110-4.
38. Kim, S. S. 2005. The world's largest (82-in.) TFT-LCD. *Society for Information Display Symposium Digest of Technical Papers* 36:1842–1847.
39. Chiang, K. H. F., Wu, S. T., and Chen, S. H. 2002. Fringing field effect of the liquid-crystal-on-silicon devices. *Japanese Journal of Applied Physics* 41:4577–4585.
40. Bahadur, B. 1990. *Liquid Crystals: Applications and Uses*. Singapore: World Scientific Press.
41. Chigrinov, V. G. 2010. Liquid crystal applications in photonics. *Frontiers of Optoelectronics in China* 3(1):103–107.
42. Wen, C. H., Gauza, S., and Wu, S. T. 2005. Photostability of liquid crystals and alignment layers. *Journal of the Society for Information Display* 13:805–811.
43. Khoo, I. C., and Wu, S. T. 1993. *Optics and Nonlinear Optics of Liquid Crystals*. Singapore: World Scientific.
44. Li, J., Wen, C.-H., Gauza, S., Lu, R., and Wu, S.-T. 2005. Refractive indices of liquid crystals for display applications. *Journal of Display Technology* 1:51–61.
45. Yilmaz, Y. O., Demir, A., Kurt, A., and Serpengüzel, A. 2005. Optical channel dropping with a silicon microsphere. *IEEE Photonics Technology Letters* 17:1662–1664.
46. Serpengüzel, A., Kurt, A., and Ayaz, U. K. 2008. Silicon microspheres for electronic and photonic integration. *Photonics and Nanostructures—Fundamentals and Applications* 6:179–182.
47. Serpengüzel, A., and Demir, A. 2008. Silicon microspheres for near-IR communication applications. *Semiconductor Science and Technology* 23:064009.

48. Yüce, E., Gürlü, O., and Serpengüzel, A. 2009. Optical modulation with silicon microspheres. *IEEE Photonics Technology Letters* 21:1481–1483.
49. Yilmaz, H., and Serpengüzel, A. 2011. Electro-optical modulation with silicon microspheres in liquid crystal. In *Proceedings of SPIE 8069 on Integrated Photonics: Materials, Devices, and Applications*, A. Serpengüzel, G. C. Righini, and A. Leipertz (Eds.). pp. 80690L–80690L-5 Bellingham, WA: SPIE.
50. Murib, M. S., Yüce, E., Gürlü, O., and Serpengüzel, A. 2014. Polarization behavior of elastic scattering from a silicon microsphere coupled to an optical fiber. *Photonics Research* 2:45–50.
51. Yüce, E., Gürlü, O., Thursby, G. J., and Serpengüzel, A. 2014. Dynamical electrical tuning of a silicon microsphere: Used for spectral mapping of the optical resonances. *Applied Optics* 53:6181–6184.
52. Wang, P., Lee, T., Ding, M., Dhar, A., Hawkins, T., Foy, P., Semenova, Y., Wu, Q., Sahu, J., Farrell, G., Ballato, J., and Brambilla, G. 2012. Germanium microsphere high-Q resonator. *Optics Letters* 37:728–730.
53. Lorenz, L. 1898. Sur la lumière réfléchié et réfractée par une sphère (surface) transparente. In: “Oeuvres scientifiques de L. Lorenz,” revues et annotées par H. Valentiner (French), Copenhagen: Tome Premier, Libraire Lehmann & Stage, pp. 403–529.
54. Mie, G. 1908. Beiträge zur optik trüber medien, speziell kolloidaler metallösungen. *Annalen der Physik* 25:377–445.
55. Chýlek, P. 1976. Partial-wave resonances and the ripple structure in the Mie normalized extinction cross section. *Journal of the Optical Society of America* 66:285–287.
56. Popat, K. C., and Desai, T. A. 2004. Poly(ethylene glycol) interfaces: An approach for enhanced performance of microfluidic systems. *Biosensors and Bioelectronics* 19:1037–1044.

Biographies

Huzyefe 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.

Hasan Yılmaz received his B.Sc. degree in Physics Engineering from Istanbul Technical University in 2008. He received his the M.Sc. degree in Materials Science and Engineering at Koç University in 2011, where he worked on “Optical Resonances of Glass Microspheres in Amorphous and Crystalline Liquids” with Prof. Ali Serpengüzel at the Microphotonics Research Laboratory. In 2015, he received his Ph.D. degree from University of Twente, for his work on “Advanced Optical Imaging with Scattering Lenses,” with Prof. Allard Mosk. He is currently a Postdoctoral Research Associate at University of Twente.

Mohammed Sharif Murib received his B.Sc. degree in Physics from Lebanese University Hadath in 2005. He received his M.Sc. degree in Physics from Koç University in 2009, where he worked with Prof. Ali Serpengüzel at the Microphotonics Research Laboratory on elastic light scattering from microspheres. He received his Ph.D. degree from Hasselt University in 2014, where he worked in the BIOSensor Group at the Institute for Materials Research with Prof. Patrick Wagner on bioelectronics and biophotonic sensors. Currently, he is a faculty member in American University of the Middle East in Kuwait.

Ali Serpengüzel received his Ph.D. degree from Yale University. He is currently a professor and the director of the Microphotonics Research Laboratory at Koç University. His current research

focuses on silicon photonics, optical microcavities, and waveguides toward applications in optical fiber communications. Other research interests include optical spectroscopy in complex media, nanophotonics, linear and nonlinear optics, and laser diagnostics toward applications in remote sensing and combustion. He is an SPIE fellow, IEEE and OSA senior member, and Sigma-Xi member.