

## Optical coupling and transport phenomena in chains of spherical dielectric microresonators with size disorder

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The optical transmission properties of chains or circuits of touching polystyrene microspheres with sizes in the 3–20  $\mu\text{m}$  range and a size dispersion of  $\sim 1\%$  are studied. The dye-doped spheres with fluorescent peaks due to whispering gallery modes were attached to one end of the chains. The effects of optical transport were detected using spatially resolved scattering spectroscopy. The attenuation was shown to be  $\sim 3$  to 4 dB per sphere for the modes with the best transport properties. A mechanism for the observed transport is suggested based on the formation of strongly coupled photonic modes in the systems of randomly detuned resonators with size disorder. It is shown that such circuits possess broad bandpass waveguiding characteristics essential for applications in integrated all-optical network devices. © 2004 American Institute of Physics.  
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During the past two decades there has been a considerable interest in the optical properties of dielectric microspheres. They are readily available cavities exhibiting whispering gallery mode (WGM) resonances<sup>1–12</sup> with high quality factors ( $Q > 10^4$  for spheres with diameters  $D > 4 \mu\text{m}$ ). This interest stemmed from applications in cavity quantum electrodynamics,<sup>4</sup> ultranarrow spectral filtering,<sup>5–8</sup> and low-threshold lasing.<sup>9,10</sup> Recent proposals of coupled resonator optical waveguides (CROW)<sup>13–15</sup> and high order optical filters<sup>16</sup> stimulated interest in systems of optically coupled microspheres such as linear chains,<sup>17,18</sup> two-dimensional (2D) arrays,<sup>19</sup> or three-dimensional crystal structures.<sup>20</sup> In these systems a “photon hopping” transport between adjacent spheres should occur at the frequencies of WGMs, providing the possibility of manipulating light paths as well as light dispersion<sup>21</sup> on a microscopic scale. The regime of strong coupling between two microspheres with marked normal mode splitting was observed<sup>22,23</sup> in the case of two identical spheres. The performance of real physical CROW structures is dependent on the size and positional disorder of resonators which can have a profound, but not very well studied, effect on optical transport.

In the present work we study optical transport in disordered ( $\sim 1\%$  size dispersion) chains of polystyrene microspheres. To evanescently couple light into such chains we used micromanipulated fluorescent (FL) dye-doped spheres with emission peaks due to WGMs resonances. The effects of optical transport through the chain were detected using spatially resolved scattering spectroscopy. We show that in contrast to CROWs which are transparent only at the resonant frequencies when perfectly ordered, our disordered circuits operate in a strongly detuned regime with broad spectral transmission function and an attenuation of about 3–4 dB per sphere for the modes with the best transport properties.

Aqueous suspensions of polystyrene spheres (Duke Scientific Corp.) with mean diameters in a  $3 \mu\text{m} \leq D \leq 20 \mu\text{m}$  range and standard  $\sim 1\%$  size dispersion were used in the structural fabrication. Initially we used a technique of mi-

crofluidic self-assembly of the microspheres on a lithographically patterned substrate<sup>24</sup> as an inexpensive and fast method of producing chains on very large areas ( $\sim 1 \text{mm}^2$ ) on the substrate, see typical results in Fig. 1(a). It was found however that this technique can lead to the occurrence of uncontrollable gaps between the spheres caused by the roughness of sidewall surfaces of the grooves, as illustrated in Fig. 1(a). For this reason we employed a technique based on the micromanipulation of dried spheres on a flat substrate using a tapered optical fiber probe. This method allows one to create structures which are self-supported by electrostatic

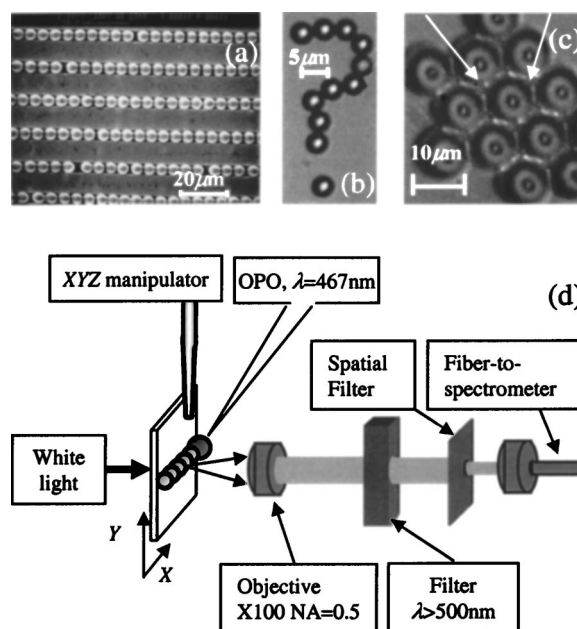


FIG. 1. (a) SEM image of 1D chains of 5  $\mu\text{m}$  spheres self-assembled in trenches etched in a Si substrate. (b) Optical image of structure obtained by micromanipulation of 5  $\mu\text{m}$  spheres. (c) White light image of 2D array of 10  $\mu\text{m}$  dye-doped spheres on the glass substrate. Under additional photoexcitation with  $\lambda = 467 \text{ nm}$  one can see high  $Q$  modes excited at the equatorial plane of the array as white hexagonal shapes decorating the spheres (shown by arrows). (d) Experimental setup for spatially resolved spectroscopic measurements.

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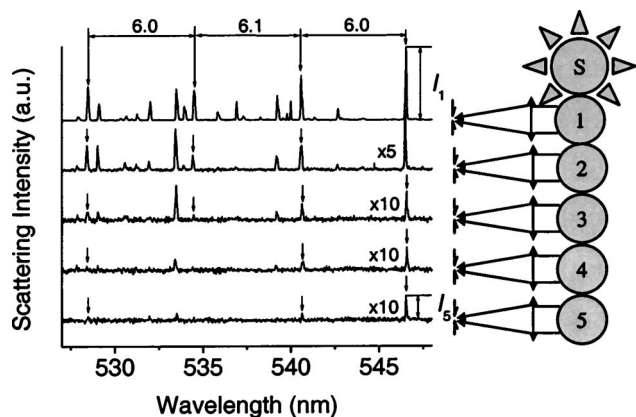


FIG. 2. Scattering spectra obtained from undoped  $9 \mu\text{m}$  spheres (1–5) coupled to a source of light (dye-doped  $10 \mu\text{m}$  sphere S). The signal was detected from each sphere using spatial filter with the size of the hole matching the size of the image of sphere. The scattering peaks originate from the WGMs resonances in the S sphere. The attenuation was estimated by comparing the intensity of the scattering peaks in different spheres, as illustrated by peaks  $I_1$  and  $I_5$  ( $\lambda=546.6 \text{ nm}$ ) for the first and fifth undoped spheres in the chain.

forces on the surface of the glass substrate, as seen in Fig. 1(b).

To couple light into such chains we used micromanipulated sources of light, specifically dye-doped FL polystyrene microspheres with  $D=10$  or  $5 \mu\text{m}$ . The spheres were pumped at the center of the absorption band of the dye (467 nm) by a tunable OPO system with a repetition frequency of 20 Hz and pulse duration of 20 ns. The FL spectra of the dye-doped spheres display multiple peaks in the 500–560 nm range due to the WGMs resonances in spherical resonators characterized by radial ( $n$ ), angular ( $l$ ), and azimuthal ( $m$ ) quantum numbers<sup>11,12</sup> for transverse electric and magnetic field modes. The excitation power was selected to be above the lasing threshold<sup>23</sup> for the WGMs peaks.

The orientation of the modes excited in the 2D arrays of touching doped spheres was directly visualized using FL imaging, as illustrated in Fig. 1(c). The spheres are visible due to additional weak white light illumination through the glass substrate. The white hexagonal shapes (indicated by arrows) decorating the spheres appear only under pumping conditions as a result of the excitation of modes with high  $Q$  factors close to the surface of the spheres. These modes are seen in the top view geometry because of scattering in the vertical direction. The hexagonal shapes are seen only if the top view image ( $\times 100$ , Mitutoyo objective with high numerical aperture,  $\text{NA}=0.5$ ) is focused on the equatorial plane of these  $10 \mu\text{m}$  spheres with a  $1 \mu\text{m}$  accuracy which confirms the horizontal orientation of these modes. The occurrence of the modes with significant spatial overlap between electromagnetic fields in different spheres indicates the possibility of strong coupling of WGMs in touching spheres.

To study the optical transport in long one-dimensional (1D) chains of undoped spheres we attached the local source of light (S sphere) to the one end of the chain and employed spatially resolved spectroscopy to detect light scattered by each undoped sphere (1–5), as schematically illustrated in Figs. 1(d) and 2. The scattering spectra represent a series of spectrometer resolution limited ( $\sim 0.15 \text{ nm}$ ) peaks which originated from the WGM resonances in S sphere. These peaks can reach the undoped spheres (1–5) only as a result of

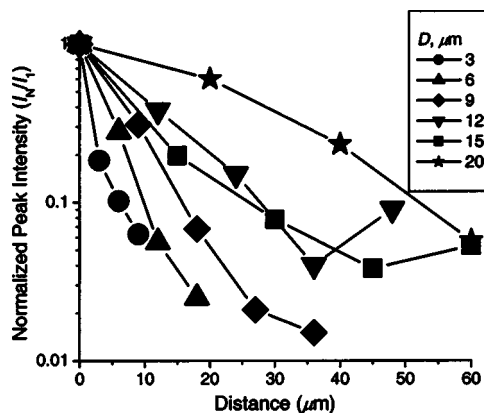


FIG. 3. Dependency of the intensity of scattering peaks produced by different spheres ( $N=1, 2, 3, \dots$ ) along the chain normalized on the intensity of the same peak in the first undoped sphere [ $I_N(\lambda)/I_1(\lambda)$ ] as a function of the distance between the centers of these spheres. The plot demonstrates attenuation  $\sim 3\text{--}4 \text{ dB}$  per sphere for the peaks with the best transport properties for  $D$  in  $3\text{--}20 \mu\text{m}$  range.

propagation inside the spheres and through the points of contact between them. This can be proved by removing a single sphere from the chain which completely interrupts the transport to the separated part of the chain. Since the efficiency of the collection of the scattered light was practically identical for each sphere the ratio of the intensities of the scattering peaks [ $I_N(\lambda)/I_M(\lambda)$ ] in different spheres ( $N, M$ ) allows one to estimate the attenuation of the propagating modes. This is illustrated in Fig. 2 where the ratio of signals (0.034) measured for a peak at  $\lambda=546.6 \text{ nm}$  from the fifth and first undoped spheres corresponds to average attenuation of 3.7 dB per sphere. The attenuation varies from mode to mode however the peaks with the best propagating properties in many cases can be identified with fundamental modes ( $l=m$ ) in the S sphere, as illustrated in Fig. 2 by a series of peaks with 6.0–6.1 nm separations expected<sup>25</sup> given the free spectral range of a  $10 \mu\text{m}$  S sphere.

Since the S sphere possesses not only the evanescent fields but also radiative and scattering modes, one can argue that the possible mechanism of such optical transport can be connected with the formation of localized “nanoscale photonic jets”<sup>26</sup> at the shadow-side of each sphere illuminated by a plane wave. In this mechanism the chain of spheres operates as a series of nonevanescingly coupled microlenses for such modes. By the nature of focusing effect the efficiency of optical transport in this mechanism should be strongly dependent on the size of the spheres.

In order to study the size dependence of the observed effects we performed attenuation measurements for different chains with sphere sizes varying in  $3\text{--}20 \mu\text{m}$  range, as illustrated in Fig. 3. For each chain we selected peaks with the best transport properties. The peak intensity measured from the  $N$ th sphere along the chain was normalized by that for the first undoped sphere and plotted as a function of the distance between centers of these spheres. The data demonstrate that the attenuation per sphere is  $\sim 3\text{--}4 \text{ dB}$  independent of the size of the spheres. This observation is not consistent with the photonic jet<sup>26</sup> mechanism mentioned above.

A more likely explanation of the observed transport is related to the formation of strongly coupled molecular modes or crystal band structures similar to that observed<sup>27,28</sup> in coupled semiconductor microcavities. In dielectric spheres

due to extremely high  $Q$  factors of their uncoupled WGM resonances the exact resonance conditions are improbable in the chains when  $\sim 1\%$  size variations occur. The random detuning ( $\sim 20$  meV) between uncoupled resonances significantly exceeds their linewidths ( $< 0.7$  meV). It is important to note however that in the strong coupling regime<sup>29</sup> such detuned states can still form spatially extended coherently coupled molecular modes. Due to the fact that on-resonance normal mode splitting<sup>22</sup> ( $\sim 14$  meV for  $D=4 \mu\text{m}$ ) is comparable to the random detuning the fraction of the eigenstates (WGMs in individual spheres) in the coupled modes of the system is significant. The eigenstates of the S sphere can also be coupled to such molecular states by the same mechanism even for detuned modes with different numbers<sup>22</sup> if their orbits have a substantial spatial overlap close to the point where the spheres touch.

This mechanism is also consistent with decreased attenuation observed for the end sphere in the chains, as illustrated in Fig. 3. For 12 and 15  $\mu\text{m}$  sphere chains we even observed increased peaks from the end sphere compared to the preceding sphere. This effect can be explained by the fact that the edge resonators can be considered as defects or "surface states" obtained as a result of termination of the 1D crystal lattice formed by the spheres. The electric-field distribution of the corresponding modes has a maximum<sup>28</sup> at the edge resonators. These modes can also be strongly coupled to the molecular states of the entire chain thus explaining stronger peaks observed from the end sphere.

In summary, long-range propagation effects were observed in slightly disordered chains of polystyrene microspheres. The optical transport properties are interpreted in terms of coupling between WGM resonances with random detuning. These results indicate the feasibility of developing waveguides based on using high quality resonators with size and positional disorder. In contrast to resonant CROW structures such waveguides possess broad bandpass transmission characteristics for evanescently coupled signals. These waveguides are important for developing functional circuits integrated on a single chip including optical buffers and delay lines, nonlinear elements, and sensors.

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- <sup>1</sup>For a review see articles in *Optical Processes in Microcavities*, edited by R. K. Chang and A. J. Campillo (World Scientific, Singapore, 1996).
- <sup>2</sup>R. E. Benner, P. W. Barber, J. F. Owen, and R. K. Chang, *Phys. Rev. Lett.* **44**, 475 (1980).
- <sup>3</sup>V. B. Braginsky, M. L. Gorodetsky, and V. S. Ilchenko, *Phys. Lett. A* **137**, 393 (1989).
- <sup>4</sup>A. J. Campillo, J. D. Eversole, and H.-B. Lin, *Phys. Rev. Lett.* **67**, 437 (1991).
- <sup>5</sup>S. Schiller and R. L. Byer, *Opt. Lett.* **16**, 1138 (1991).
- <sup>6</sup>A. Serpengüzel, S. Arnold, and G. Griffel, *Opt. Lett.* **20**, 654 (1995).
- <sup>7</sup>M. L. Gorodetsky, A. A. Savchenkov, and V. S. Ilchenko, *Opt. Lett.* **21**, 453 (1996).
- <sup>8</sup>M. Cai, O. Painter, and K. J. Vahala, *Phys. Rev. Lett.* **85**, 74 (2000).
- <sup>9</sup>L. Colot, V. Lefevre-Seguin, M. Brune, J.-M. Raimond, and S. Haroche, *Europhys. Lett.* **23**, 327 (1993).
- <sup>10</sup>S. M. Spillane, T. J. Kippenberg, and K. J. Vahala, *Nature (London)* **415**, 621 (2002).
- <sup>11</sup>B. Möller, M. V. Artemyev, and U. Woggon, *Appl. Phys. Lett.* **80**, 3253 (2002).
- <sup>12</sup>B. Möller, U. Woggon, M. V. Artemyev, and R. Wannemacher, *Appl. Phys. Lett.* **83**, 2686 (2003).
- <sup>13</sup>N. Stefanou and A. Modinos, *Phys. Rev. B* **57**, 12127 (1998).
- <sup>14</sup>A. Yariv, Y. Xu, R. K. Lee, and A. Scherer, *Opt. Lett.* **24**, 711 (1999).
- <sup>15</sup>S. Mookherjea and A. Yariv, *IEEE J. Sel. Top. Quantum Electron.* **8**, 448 (2002).
- <sup>16</sup>B. E. Little, S. T. Chu, H. A. Haus, J. Foresi, and J.-P. Laine, *J. Lightwave Technol.* **15**, 998 (1997).
- <sup>17</sup>M. D. Barnes, S. M. Mahurin, A. Mehta, B. G. Sumpter, and D. W. Noid, *Phys. Rev. Lett.* **88**, 015508 (2002).
- <sup>18</sup>H. Furukawa and K. Tenjimabayashi, *Appl. Phys. Lett.* **80**, 192 (2002).
- <sup>19</sup>T. Kondo, M. Hangyo, S. Yamaguchi, S. Yano, Y. Segawa, and K. Ohtaka, *Phys. Rev. B* **66**, 033111 (2002).
- <sup>20</sup>H. Guo, H. Chen, P. Ni, Q. Zhang, B. Cheng, and D. Zhang, *Appl. Phys. Lett.* **82**, 373 (2003).
- <sup>21</sup>J. E. Heebner, R. W. Boyd, and Q.-H. Park, *Phys. Rev. E* **65**, 036619 (2002); *J. Opt. Soc. Am. B* **19**, 722 (2002).
- <sup>22</sup>T. Mukaiyama, K. Takeda, H. Miyazaki, Y. Jimba, and M. Kuwata-Gonokami, *Phys. Rev. Lett.* **82**, 4623 (1999).
- <sup>23</sup>Y. Hara, T. Mukaiyama, K. Takeda, and M. Kuwata-Gonokami, *Opt. Lett.* **28**, 2437 (2003).
- <sup>24</sup>G. A. Ozin and S. M. Yang, *Adv. Funct. Mater.* **11**, 95 (2001).
- <sup>25</sup>D. Morrish, X. Gan, and M. Gu, *Appl. Phys. Lett.* **81**, 5132 (2002).
- <sup>26</sup>Z. Chen, A. Taflöv, and V. Backman, *Opt. Express* **12**, 1214 (2004).
- <sup>27</sup>M. Bayer, T. Gutbrod, A. Forchel, T. L. Reinecke, P. A. Knipp, R. Werner, and J. P. Reithmaier, *Phys. Rev. Lett.* **83**, 5374 (1999).
- <sup>28</sup>V. Zhuk, D. V. Regelman, D. Gershoni, M. Bayer, J. P. Reithmaier, A. Forchel, P. A. Knipp, and T. L. Reinecke, *Phys. Rev. B* **66**, 115302 (2002).
- <sup>29</sup>A. Armitage, M. S. Skolnick, V. N. Astratov, D. M. Whittaker, G. Panzarini, L. C. Andreani, T. A. Fisher, J. S. Roberts, A. V. Kavokin, M. A. Kaliteevski, and M. R. Vladimirova, *Phys. Rev. B* **57**, 14877 (1998).