

Remote Activation of Capsules Containing Ag Nanoparticles and IR Dye by Laser Light

Andre G. Skirtach,^{*,†,‡} Alexei A. Antipov,^{†,§} Dmitry G. Shchukin,[†] and Gleb B. Sukhorukov[†]

Max-Planck Institute of Colloids and Interfaces, Potsdam/Golm, Germany, Photonics TP Inc., Ottawa, Ontario, Canada, and Plasmachem GmbH, Mainz, Germany

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We present a novel method for remote release of an encapsulated material from polyelectrolyte capsules based on laser light illumination. Two different components were introduced in the polyelectrolyte shells of PAH/PSS capsules—either Ag nanoparticles or IR dye—to induce absorption of light. Under laser illumination the capsules containing Ag nanoparticles or IR dye were deformed or cut, thus providing a venue for remote release of encapsulated materials. The experiments were conducted with a low-power near-infrared continuous-wave laser diode.

Microcapsules offer effective means for delivery of encapsulated compounds.^{1,2} Recently, a novel method, based on layer-by-layer adsorption of oppositely charged species³ on colloidal particles,⁴ has been introduced for encapsulation of a variety of chemical and biological substances. Its main advantage is the ability to adjust the desired composition of the shells of capsules by, for example, alternatively depositing polyelectrolytes and nanoparticles.^{5,6} A variety of materials were successfully encapsulated ranging from enzymes and DNA to rather small dye molecules.^{7,8} Remote activation of encapsulated materials by deforming or cutting through the capsule is essential for controlling biochemical reactions. Once the capsules containing catalysts, enzymes, or drugs are delivered to a site for a chemical or biological reaction, it is necessary to activate its content or release the encapsulated material remotely. In this work we describe a novel technique of remote activation of encapsulated material by laser light irradiation.

Laser-driven chemical reactions,⁹ ablative decomposition of solid materials and polymers,¹⁰ study of the reaction kinetics by time-resolved laser spectroscopy,¹¹ optical trapping and manipulation of microparticles,¹² and ac-

tivation of microcomponents with light¹³ are some of the examples of applications of lasers. Electronic control of DNA hybridization is possible through the interaction of radio frequency magnetic field with gold nanoparticles bound to DNA strands.¹⁴ A nanosecond 355 nm UV laser has been previously applied for ablation of pyrene/toluene filled droplets.¹⁵ In that work a droplet was optically trapped using a continuous-wave (CW) laser source and then was subjected to an intense laser pulse which opened or destroyed the droplet. In a different application area the effects of light on biological tissue have been extensively studied in PDT (photodynamic therapy) to stimulate apoptosis in the targeted cells by a laser. In the past, substantial research in this area has concentrated on the ability of photosensitizers, like porphyrin, to induce and enhance oxidation reactions. Recently gold nanoparticles adsorbed on cells were used to enhance absorption of light and facilitate the destruction of cells.¹⁶ In both of these studies, the energy deposited by the laser was relatively low but the peak pulsed intensities required for these processes were high. In addition to that, in both cases the excitation wavelength was in the visible/UV range. We demonstrate here that remote release of the encapsulated compound can be performed with a low power continuous wave laser with wavelength in the near-infrared part of the spectrum.

Materials and Methods

* To whom coreespondence may be addressed at Abt. Grenzflächen, Max Planck Institute of Colloids and Interfaces, Am Mühlenberg 1, D-14476 Golm, Germany. Phone (North America): (613)-262-8633. Phone (Europe): +49-331-567-9429. Fax: +49-331-567-9202. E-mail: ASkirtach@ieee.org.

† Max-Planck Institute of Colloids and Interfaces.

‡ Photonics TP Inc.

§ Plasmachem GmbH.

(1) Lim, F. In *Biomedical Applications of Microencapsulation*; CRC Press: Boca Raton, FL, 1984.

(2) Ai, H.; Jones, S. A.; de Villiers, M. M.; Lvov, Y. M. *J. Controlled Release* **2003**, *86*, 59.

(3) Decher, G. *Science* **1997**, *277*, 1232.

(4) Sukhorukov, G. B.; Donath, E.; Lichtenfeld, H.; Knippl, E.; Knippl, M.; Budde, A.; Möhwald, H. *Colloids Surf. A* **1998**, *137*, 253.

(5) Sinani, V. A.; Koktysh, D. S.; Yun, B. G.; Matts, R. L.; Pappas, T. C.; Motamedi, M.; Thomas, S. N.; Kotov, N. A. *Nano Lett.* **2003**, *3*, 1177.

(6) Caruso, F. *Chem. Mater.* **2002**, *14*, 1909.

(7) Donath, E.; Sukhorukov, G. B.; Caruso, F.; Davies, S. A.; Möhwald, H. *Angew. Chem., Int. Ed.* **1998**, *37*, 2202.

(8) Möhwald, H.; Donath, E.; Sukhorukov, G. B. In *Multilayer Thin Films. Sequential Assembly of Nanocomposite Materials*; Decher, G., Schlenoff, J. B., Eds.; Wiley-VCH: Weinheim, 2002.

(9) Zare, R. N. *Science* **1998**, *279*, 1875.

(10) Kokai, F.; Niino, H.; Yabe, A. *J. Phys. Chem. B* **1998**, *102*, 8400.

(11) Stolow, A. *Annu. Rev. Phys. Chem.* **2003**, *54*, 89.

(12) Ashkin, A. *Phys. Rev. Lett.* **1970**, *24*, 156.

Poly(sodium 4-styrenesulfonate) (PSS), ~70 kDa, poly(allylamine hydrochloride) (PAH), 50–60 kDa, IR-806 infrared dye, silver nitrate, and trisodium salt of ethylenediaminetetraacetic acid were purchased from Sigma-Aldrich (Germany). Inorganic acids, bases, and salts were obtained from Roth (Germany). Melamineformaldehyde (MF) latex particles were received from Microparticles GmbH (Germany). The water used in all experiments was prepared in a three-stage Millipore Milli-Q Plus 185 purification system and had a resistivity higher than 18.2 MΩ cm.

Preparation of Capsules Containing Silver Nanoparticles. Modification of polyelectrolyte shells with metallic

(13) Gauthier, R. C.; Tait, R. N.; Ubriaco, M. *Appl. Opt.* **2002**, *41*, 2361.

(14) Hamad-Schifferli, K.; Schwartz, J. J.; Santos, A. T.; Zhang, S.; Jacobson, J. M. *Nature* **2002**, *415*, 152.

(15) Misawa, H.; Kitamura, N.; Masuhara, H. *J. Am. Chem. Soc.* **1991**, *113*, 7859.

(16) Pitsillides, C. M.; Joe, E. K.; Wei, X.; Anderson, R. R.; Lin, C. P. *Biophys. J.* **2003**, *84*, 4023.

nanoparticles was performed by Tollens probe reaction (silver mirror reaction) on the surface of polyelectrolyte multilayer-coated latexes.¹⁷ Precoating with polyelectrolyte multilayers was done as follows: 1800 μL of 1.5% suspension of 5 μm MF latexes in 0.5 M NaCl aqueous solution was mixed with 200 μL of 5 mg/mL PSS solution. Fifteen minutes of incubation was followed by triple washing with water and centrifugation. Particles coated with one PSS layer reversed their charge from positive to negative and could be coated by the PAH layer in a similar manner. The adsorption circle was repeated until two (PSS/PAH) bilayers were formed. As a second step, the metallic layer had to be assembled onto the precoated latexes. The suspension of the shells was mixed with 40 μL of acetaldehyde and put into an ultrasonic bath, followed by slow dropwise addition of 100 μL of 5% freshly prepared $[\text{Ag}(\text{NH}_3)_2]\text{NO}_3$. After 60 min the shells were washed by five centrifugation cycles. The obtained coating could be made stable against desorption of silver particles by further coating with two additional (PSS/PAH) bilayers. Hollow capsules having the final (PSS/PAH)₂-Ag-(PSS/PAH)₂ structure were obtained by dissolution of MF cores in 0.1 M HCl and cleaning by five centrifugation circles.

Preparation of Multilayer Capsules Containing an IR-806 Dye. Multilayer capsules constructed from IR dye and polyelectrolyte were produced by layer-by-layer adsorption. PAH was used as a polycation and the IR-806 dye as a low-molecular weight anion. Fifteen micrometer CaCO_3 particles¹⁸ were used as templates. A 1800 μL quantity of 2% particles in aqueous suspension were mixed with 200 μL of 2 mg/mL PAH solution. After 15 min of adsorption, the rest of the polyelectrolyte was removed by triple washing with water and centrifugation. The second layer was formed after incubation of the obtained suspension with 100 μL of IR-806 aqueous solution and cleaning by triple centrifugation. The adsorption cycle was repeated several times until the (PAH/IR-806)₄PAH shell was formed. Carbonate cores were dissolved in 0.2 M EDTA solution with pH 7.1, and the obtained capsules were washed and stored in water.

Capsules with IR-806 Dye Only on the Outer Layer. The PAH/PSS capsules, assembled on the surface of MnCO_3 template particles of 4 μm diameter by the layer-by-layer approach,^{2,7} were immersed in a 0.3×10^{-2} M solution of IR-806 dye, and the mixture was subjected to shaking for 2 h to complete adsorption of the dye in the capsule. Subsequently, the capsules were centrifuged and washed out with deionized water. Resulting PAH/PSS capsules with IR-806 dye absorb light for wavelengths between 700 and 900 nm, with the peak located at 806 nm.

Optical Setup. The schematic diagram of the setup is shown in Figure 1. A CW laser diode at 830 nm with optical power up to 80 mW was used in the experiments. The collimated laser beam was focused onto the sample through a microscope objective, 100 \times magnification N.A. = 1.25 (Edmund Scientific, Commercial Grade). The sample was positioned in the field of view by a micrometer resolution XYZ stage. Illumination was made in transmission mode using a 150 W white light source, and the images were recorded by a charge coupled device (CCD) camera connected to a computer. The solution containing the capsules was deposited onto a microscope slide under the microscope objective. Laser intensity was measured incident upon the microscope objective by a Newport-1830C powermeter. The absorption spectra were measured by a Varian, CARY, 50 Conc UV-vis spectrophotometer.

Results and Discussion

It is vital that during remote catalyst or drug release by a laser source the light affects only the shell of the capsule while remaining nondestructive to the encapsulated compound and the surrounding environment. The main obstacle in this area—heating in the focus of the microscope objective—was the subject of extensive research. It is unavoidable to heat the local environment by tightly focusing the laser beam, so it is imperative to

(17) Antipov, A. A.; Sukhorukov, G. B.; Fedutik, Y. A.; Hartmann, J.; Giersig, M.; Möhwald, H. *Langmuir* **2002**, *18*, 6687.

(18) Antipov, A. A.; Shchukin, D.; Fedutik, Y.; Petrov, A. I.; Sukhorukov, G. B.; Möhwald, H. *Colloids Surf., A* **2003**, *224*, 175.

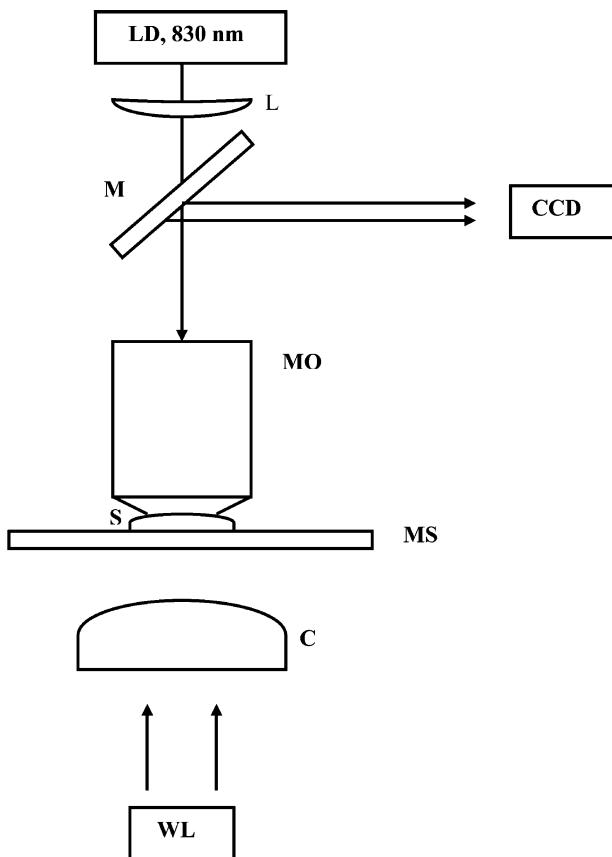


Figure 1. The experimental setup used in the experiments. A laser diode (LD), 830 nm, is collimated by the lens (L) and focused through a microscope objective (MO) onto the sample (S). The sample is located on the microscope cover slide (MS). The illumination was made by white light (WL) in transmission through a condenser (C). White light, transmitted through the microscope objective, was reflected by a dichroic mirror (M) onto a CCD camera.

optimize the heat-inducing parameters. Choosing the laser wavelength that avoids the main absorption peaks of encapsulated material and the environment can significantly reduce the adverse heating effects. Near-infrared laser diodes are well suited to work with biological matter and water. In our case the excitation wavelength, 830 nm, is chosen in the biologically “friendly” window (700–1000 nm) where the absorption of tissue, biomedical substances, and water is minimal. In fact, volume heating of water in the focus of the microscope objective is shown to be less than 0.5 K at 850 nm with laser powers up to 100 mW and with exposures less than 1 s.¹⁹ Although in our experiments the samples were illuminated for less than 1 s, we have not observed any effects on aqueous solution in which the capsules were immersed even at prolonged exposures of the samples to the laser beam.

Three types of capsules were used in the experiments: Ag nanoparticle containing, IR-806 dye containing, or doped capsules and PAH/PSS control capsules (no dopant). Neither PSS nor PAH exhibits any absorption in the near-IR part of the spectrum. Corollary, PAH/PSS capsules do not exhibit any effect to laser light illumination. Introduction of a dopant, like metal nanoparticles or IR dyes, into the shells of capsules stimulates absorption of energy. If this energy is sufficient to induce a rupture in the shell of capsules, then the encapsulated material is released.

Additionally to PAH/PSS capsules, we have done experiments with two other types of capsules—PAH/PSS

(19) Schönle, A.; Hell, S. W. *Opt. Lett.* **1998**, *23*, 325.

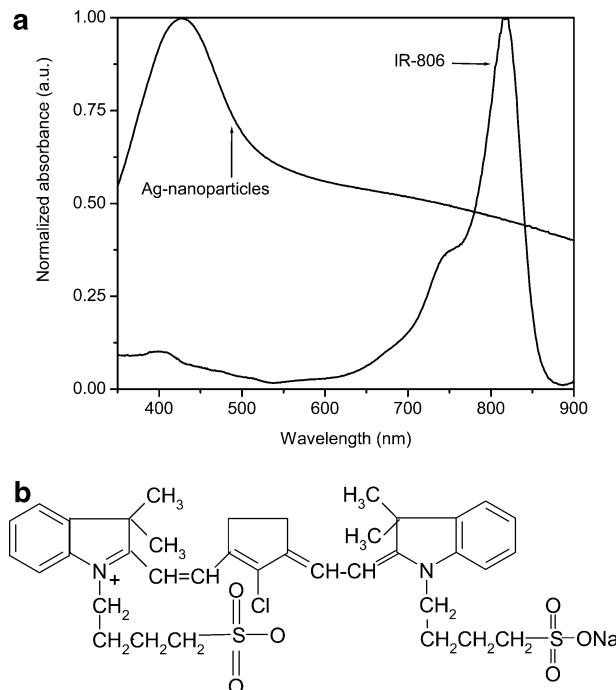


Figure 2. (a) Absorption spectra of Ag nanoparticles and IR-806 dye. (b) Chemical formula of IR-806 dye.

capsules containing Ag nanoparticles and PAH/PSS capsules with IR-806 dye. The absorption spectra of Ag nanoparticles and IR-806 dye, normalized to their respective peaks, and the chemical structure of IR-806 are shown in parts a and b of Figure 2, respectively. The absorption spectra of capsules are difficult to measure due to strong scattering, so the spectra were obtained in solutions. The absorption spectrum of Ag nanoparticles was measured in a colloidal solution obtained by photoreduction of AgNO_3 in the presence of PSS; it is consistent with the earlier work.²⁰ The size distribution of the Ag nanoparticles, as revealed by transmission electron microscopy (TEM) imaging, was the same as that obtained on capsules. The absorption spectrum of IR-806 dye was obtained in the solution. Absorption bands of silver sols in the 380–500 nm range are attributed to a collective oscillation of the electron gas in the particles of nanometer scale ($\sim 8 \text{ nm}$, plasmon absorption).²¹ The wavelength of plasmon absorption bands for silver nanoparticles shifts to the red side of the spectrum and, further, to the near-IR region with the increasing particle size.²² Ag nanoparticles serve as absorbing centers in the shells of capsules as shown in Figure 3a, which presents TEM images. It can be seen from this figure that the Ag nanoparticles are distributed throughout the shell of the capsules. Figure 3b shows a magnified section of the capsule with silver nanoparticles on its surface. Since there was no response of PAH/PSS capsules to laser light, one can conclude that energy of the laser beam is absorbed and accumulated on nanoparticles, locally heating them and inducing the rupture in the shell. This effect is similar to that observed in destruction of tumor cells containing Au nanoparticles by illuminating them with an intense laser pulse.¹⁶ There is, however, an important distinction between these two systems. In our case the laser wavelength, 830 nm, is located away from the main absorption peak of silver ($\sim 400 \text{ nm}$), while the 532 nm wavelength of the pulsed laser is located within the absorption peak of Au at 520 nm.¹⁶

We have observed the following effects: cutting through, deformation, and ablative destruction of a capsule for both Ag nanoparticle and IR-dye-doped capsules. Each of these phenomena depends on the intensity of laser light. Intensities up to 25 mW resulted in cutting through and deforming silver-nanoparticle-doped capsules. Figure 4 shows the opening of the capsule by interaction with the laser beam. It can be seen from this figure that initially, Figure 4a, the capsule is intact. The capsules shown in the background allow one to compare the location of the capsule during the experiments. Figure 4b shows the capsule, still intact, at the beginning of laser illumination together with the laser beam. In panels b and c of Figure 4 the laser beam is seen reflected from the interface of the microscope slide and the aqueous solution. The double reflection images correspond to reflection from both sides of the dichroic mirror. The snapshot in Figure 4c was taken before the laser exposure was closed. One could clearly see from Figure 4c that part of the capsule was cut and some of its pieces are shown on the left-hand side of this picture. The capsule is shown cut or opened up in Figure 4d. After the interaction with the laser, all parts of capsules appeared dark in the transmission microscope. This indicates that most Ag nanoparticles stay on the ruptured polyelectrolyte shells. The process described above can be employed for the remote release of any encapsulated material. When the laser intensity was increased above 70 mW, one could ablate the capsule or even a group of capsules resulting in its destruction.

In addition to the testing of Ag nanoparticle-containing capsules, experiments were conducted with IR-806-dye-doped capsules prepared by two different methods. In the first case multilayers of dye were deposited between the layers of PAH/PSS. Because of the multilayer composition of the shells, the capsules appeared dark in transmission microscopy and behaved similar to the Ag-nanoparticle-doped capsules. In the second case IR dye was adsorbed only on the outer layer and the capsules appeared semitransparent with a green color. Despite the fact that the wavelength of the laser diode is located inside the absorption band of the IR-806 dye, the intensity required to activate these capsules, 60 mW, was higher than that necessary for the capsules with silver nanoparticles. This is attributed to adsorption of dye molecules only on the outer layer since the capsules comprised of multilayers of the same IR-806 dye required similar intensities compared to those for silver-containing capsules. In the center of Figure 5a the capsule with IR-806 dye adsorbed on the outer layer is shown before the interaction with laser light. It can be seen from this figure that the capsule under the arrow appears circular. The same capsule is shown deformed after exposure to the laser beam with intensity of 60 mW, Figure 5b. The capsules shown above the targeted capsule (with arrow) were pushed away from the field of view during laser light illumination^{12,13} and, therefore, they do not appear in Figure 5b.

The direct comparison of capsules with Ag nanoparticles and IR dye is complicated since they represent two fundamentally different systems in regard to their interaction with light. The effect observed for Ag-nanoparticle-doped capsules stems from direct local heating of nanoparticles,¹⁶ while in the case of IR-dye-doped capsules it is the electronic–vibronic–phonon energy conversion²³ that induces heating which leads to the rupture of the

(20) Kreibig, U.; Vollmer, M. In *Optical Properties of Metal Clusters*; Springer-Verlag: Berlin, 1995.

(21) Henglein, A.; Linnert, T.; Mulvaney, P. *Ber. Bunsen-Ges.* **1990**, 94, 1457.

(22) Murphy, C. J.; Jana, N. R. *Adv. Mater.* **2002**, 14, 80.

(23) Sisk, N.; Kang, K.-S.; Raja, M. A.; Farahi, F. *Int. J. Optoelectron.* **1995**, 10, 95.

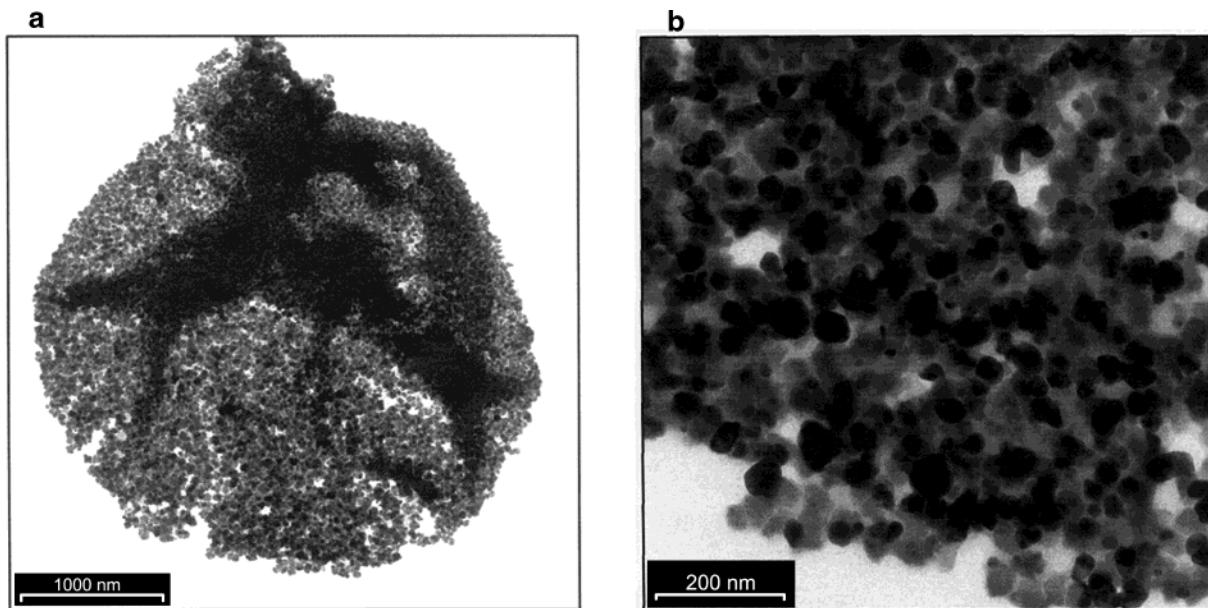


Figure 3. TEM images of the shell of the capsule with Ag-nanoparticles: (a) whole capsule and (b) a section with larger magnification.

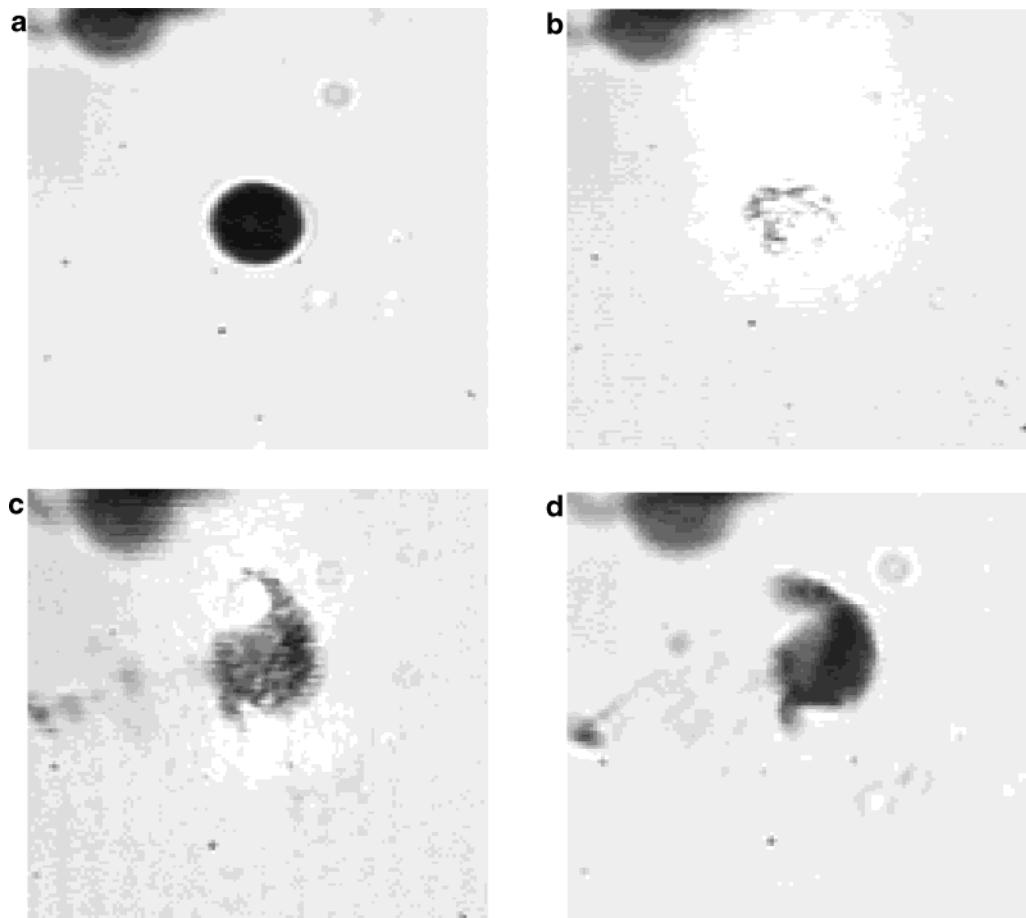


Figure 4. The Ag-nanoparticle-doped capsule is intact before the interaction (a), during the initial illumination (b), later on during the exposure (c), and after the interaction (d) with the laser beam of 25 mW. Location and morphological shape of other capsules that were not exposed to laser are shown unchanged.

shells. We note that by choosing appropriate nanoparticles and adjusting their size, one can control their absorption properties thus regulating their response to laser irradiation. In the case of IR-dye-doped capsules, the most important parameters that govern their interaction with light are the location of the absorption peak relative to

the laser wavelength and the composition of the shells of the capsules, i.e., multilayers versus single layers.

In conclusion, we have shown the feasibility of the novel method for remote release from Ag nanoparticles or IR-dye-doped polyelectrolyte capsules induced by laser light irradiation. Comparison with PAH/PSS capsules that

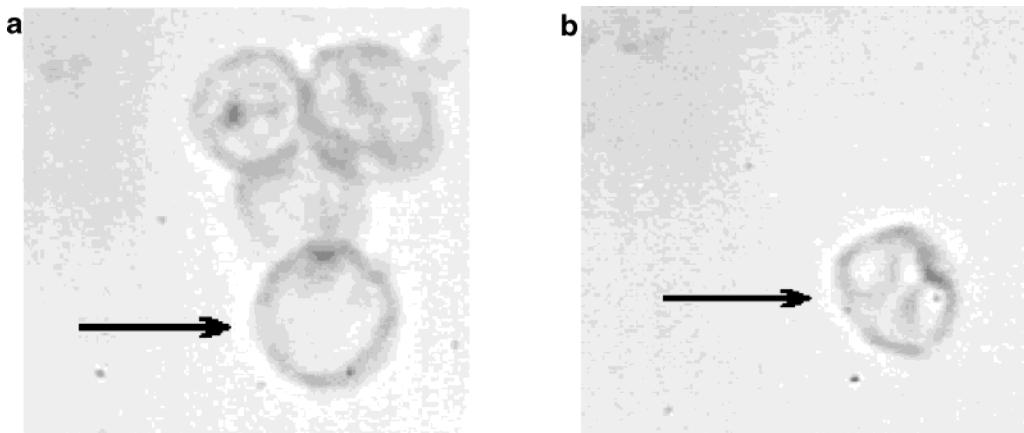


Figure 5. The IR-806-dye-doped to the outer shell of the capsules shown (a) before and (b) after the interaction with the laser beam of 60 mW. The capsules shown above the capsule with the arrow, panel a, were pushed away by the laser and are not shown in panel b.

contained no light absorbing agent indicates that the presence of a dopant like Ag nanoparticles or IR-absorbing dye is the primary cause for the rupture of polyelectrolyte shells of capsules which leads to deformation and, sequentially, to the permeability change. The rupture of the walls of capsules would result in the release of encapsulated materials. The intensity of the laser beam, absorption properties of the materials constituting the shell of the capsules, and their composition allow for control of the nature of their interaction with the laser—cutting through, deforming, or ablating them. We would like to note that the method described here could be used for

both practical applications in the area of catalyst or drug release and scientific research of the interaction of the encapsulated material with the walls of capsules.

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