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(54) Title: OPTICAL TRAPPING PARTICLE AND OPTICAL TRAPPING METHOD

(57) Abstract: An optical trapping particle (1) for optical trapping by means of an optical tweezers comprises a core particle (11) having a first refractive index and a shell (12) having a second refractive index. Thereby, the first refractive index is higher than the second refractive index. With such an optical trapping particle (1) coated with a shell (12) arranged for acting as an anti-reflection coating, during optical trapping the trap stiffness can be increased compared to an uncoated optical trapping particle.

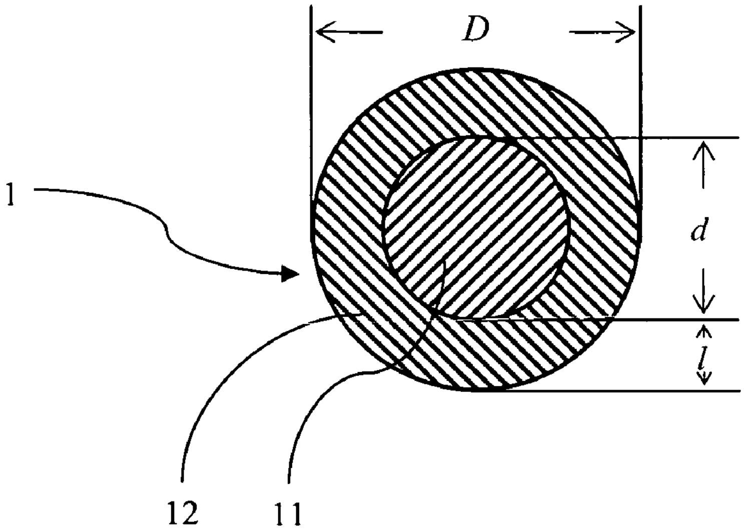

Fig. 1

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OPTICAL TRAPPING PARTICLE AND OPTICAL TRAPPING METHOD

Technical Field

The present invention relates to an optical trapping particle according to the preamble of independent claim 1 and more particularly to an optical trapping method. Such optical trapping particles can be used for optical trapping by means of an optical tweezers. Such optical trapping methods comprising the step of trapping a particle by means of an optical tweezers can be used for trapping such optical trapping particles.

Background Art

Optical trapping is widely employed in various fields of applied research such as biophysics, colloid research, micro-rheology, and physics in order to manipulate dielectric particles or other materials using optical gradient forces. For example, with optical trapping the manipulation and detection of sub-nanometer displacements for sub-micrometre and micrometer sized dielectric particles is possible. For performing optical trapping, optical tweezers are commonly preferred instruments wherein optical tweezers are also known as Photonic Force Microscopes (PFM), or simply as Optical Trap. Optical tweezers use a focused light beam to provide an attractive or repulsive optical force to physically hold and move the dielectric particles which usually are arranged in a medium such as for example in an aqueous solution. Examples of early stage embodiments of optical tweezers are described for example in US 3,808,550 A1.

In optical trapping, for example by means of an optical tweezers, the optical force induced by a focused light beam on the particle in scope is composed, in a simplified picture, of an attractive gradient force into the direction of the highest light intensity which is in the focus of the light beam, and a scattering force into the direction of light propagation. This scattering force pushes the particle away from the focus of the light beam thereby destabilizing the optical trapping. In a geometric optics picture, to first order, the scattering force is proportional to the reflectivity which scales with the square of a refractive index difference of the particle with respect to its surrounding medium, e.g. the aqueous solution. Due to Snell's law, the gradient force is to a first order approximation proportional to the refractive index difference.

Thus, for particles consisting of materials having a high relative refractive index compared to the refractive index of a medium accommodating the particles, the scattering force dominates and the particles cannot be trapped with a single laser trap, which limits the range of materials for optical trapping materials. For example, this effect is particularly important if trapped microspheres - so-called beads – are the object of interest or are used as handles for measurements. These beads often have a comparably high refractive index and as described above they can only be stably trapped by means of an optical tweezers if for the axial direction the gradient force is larger than the scattering force. This can decisively limit the possibilities of optical trapping of beads.

Furthermore, in many applications of optical trapping the power of a light beam induced by an optical trapping device, such as for example an optical tweezers, to trap a particle has to be sufficiently high to provide a suitable trapping of the particle. The induction of such a light beam often requires a comparably high amount of energy such that the operation of an according optical trapping device can be rather inefficient, or can lead to photo-interaction negatively affecting the particle, molecules adsorbed onto the particle, or the experimental configuration itself, such as for example photo-toxic interactions relevant for biological applications.

Therefore, there is a need for improved optical trapping allowing an enhanced range of applications. Particularly, there is a need for improved efficient trapping of particles consisting of a material having a comparably high relative refractive index.

Disclosure of the Invention

According to the invention this need is settled by an optical trapping particle as it is defined by the features of independent claim 1, and by an optical trapping method as it is defined by independent claim 9. Preferred embodiments are subject of the dependent claims.

In particular, the invention deals with an optical trapping particle comprising a core particle having a first refractive index (η_{core}), and a shell or coating layer, respectively, having a second refractive index (η_{shell}), wherein the first refractive index is higher than the second refractive index ($\eta_{core} > \eta_{shell}$). Core particle in this context is related to target particles to be optically trapped for example by means of an optical tweezers and, in particular, it also includes microspheres. Refractive index in this context is related to the measure of how much the speed of light is reduced by a medium compared to a reference medium which typically is vacuum.

With an optical trapping particle coated with a shell arranged for acting as an anti-reflection coating or as an index matching material according to the invention, during optical trapping the trap stiffness can be increased for example compared to an uncoated optical trapping particle of the same material as the core particle and of the same size as the total size of the coated optical trapping particle. Trap stiffness in this context is related to an inherent stiffness of the optical trapping, which is controlled by the power of a light beam induced by a trapping device, such as for example by an optical tweezers, for trapping the optical trapping particle. Particularly, trap stiffness can be defined by proportionality constant k relating the restoring force F exerted by light onto the trapped optical particle when the particle is displaced by a small distance of Δx away from its equilibrium trapping position $F=k^*\Delta x$). The trap stiffness as a function of particle diameter usually has a sharp maximum for each material and accordingly the diameter where the maximal trap stiffness is achieved is the ideal core particle diameter. Apart from the increased trap stiffness, the linear range of both a back-focal plane positional detection and a gradient force can be increased during optical trapping of an optical trapping particle according to the invention compared to uniform optical trapping particles, i.e. for example the uncoated core particle.

Thus, optical trapping particles having a comparably high refractive index can be trapped which possibly can not be trapped unless being inventively coated with a shell. Furthermore, optical trapping particles being comparably susceptible for being negatively affected by photo-interaction can be sufficiently trapped on a decreased level of light beam intensity. Also, independent of the polarization of the trapping laser the trap stiffness in the two lateral directions being arranged perpendicularly to an axis of light beam propagation can be equal.

Thereby, the optical trapping particle can particularly be an optical trapping particle suitable for optical trapping by means of an optical tweezers.

In an embodiment of the optical trapping particle according to the invention, a diameter of the core particle is greater than about 0.1 micrometer and less than about 2 micrometer. Thereby, the diameter of the core particle can particularly be greater than about 0.3 micrometer and/or the diameter of the core particle can particularly be less than about 1.5 micrometer. Such micro-sized optical trapping particles are particularly suitable for many applications of optical trapping such as for example dual trap experiments with DNA or RNA, single molecule motor protein experiments, e.g., with kinesin, or force measurements in cells.

An outer diameter of the optical trapping particle can be less than about 10 micrometer, and in particular the outer diameter of the optical trapping particle can be less than about 3 micrometer. Such optical trapping particles are advantageous in various optical trapping applications.

A thickness of the shell of the optical trapping particle can be greater than or can equal about 0.06 micrometer, particularly for optical trapping with a laser beam having a wave length in the range from about 400 nanometer to about 700 nanometer. For achieving a suitable trapping improvement effect, a minimum thickness of the shell is preferred. For example, for micro-sized particles this minimum thickness preferably is at least 0.06 micrometer when using various shell materials.

The thickness of the shell of the optical trapping particle can be greater than or can equal about 0.15 micrometer, particularly for optical trapping with a laser beam having a wave length in the range from about 700 nanometer to about 1330 nanometer. For achieving a suitable trapping improvement effect, a minimum thickness of the shell is preferred. For example, for micro-sized particles this minimum thickness preferably is at least 0.1 micrometer when using various shell materials.

Advantageously, the core particle of the optical trapping particle is made of polystyrene, titanium dioxide, diamond, zinc sulphide, vaterite, calcite lysozyme crystals, quartz, or polymethylmethacrylate (PMMA). The shell of the optical trapping particle can be made of polytetrafluoroethylene, polystyrene, silica, or polymethylmethacrylate (PMMA). Optical trapping particles made of a combination of such materials of its core and its shell, can be advantageous in various optical trapping applications and can be comparably easy to manufacture.

In a first embodiment of the optical trapping particle according to the invention, the core particle is made of polystyrene (PS) and the shell is made of silica (SiO_x). For optical trapping in a medium, e.g. water, having the same refractive index as the shell, e.g. silica (SiO_x), this optical trapping particle allows the shell to be thick enough to making the optical trapping of certain substances possible. For example, the optical trapping particle can be big enough such that molecules being connected to the optical trapping particle are not in a critical area of a laser beam while the optical trapping particle is trapped by the laser beam. Thus, such molecules being comparably susceptible for being negatively affected by photo-interaction can be trapped via the optical trapping particle.

In a second embodiment of the optical trapping particle according to the invention, the core particle is made of polystyrene (PS) and the shell is made of polytetrafluoroethylene (PTFE). Like this, if a medium in which the optical trapping particle is to trap is water, the shell is almost index matched with the medium. The coated optical trapping particle has the same properties as the core particle independent of the shell thickness. But to trap the coated optical trapping particle the core particle itself has to be trappable.

In a third embodiment of the optical trapping particle according to the invention, the core particle is made of titanium dioxide (TiO_2) and the shell is made of polystyrene (PS). Uncoated optical trapping particles of high refractive index materials such as for example titanium dioxide (TiO_2) can not be trapped in water due to a scattering force larger than the gradient force. The inventive antireflection shell or coating for example of polystyrene on a TiO_2 core can reduce the scattering force such that the coated optical trapping particle is trappable. For various shell thicknesses the coated optical trapping particle gets trappable with a comparably high trap stiffness despite the high refractive index difference of the core particle to the medium in which the optical trapping particle is to trap.

The core particle of the optical trapping particle can have a non-spherical shape. Furthermore, the core particle of the optical trapping particle can be made of a birefringent material. Such optical trapping particles can have a preferred orientation in a light beam. Thus, while being optically trapped such an optical trapping particle can be rotated by means of the light beam and improved stability can be provided.

The core particle of the optical trapping particle can also be an optical trapping particle according to invention. With such a multi-shell optical trapping particle the refractive index can shell-wise be reduced such that a more or less continuous decreasing arrangement of the refractive index is possible.

Another aspect of the invention relates to an optical trapping method comprising the step of trapping a particle by means of an optical tweezers. The optical trapping method further comprises the step of coating a core particle with a shell such that the particle being trappable by means of the optical tweezers is an optical trapping particle as described above. For coating the core particle to build up the shell, established procedures known in the art for coating micro-particles can be used.

Such an optical trapping method allows the optical trapping of optical trapping particles having a comparably high refractive index which possibly can not be trapped unless being inventively coated with a shell. Further, it allows the optical trapping of optical trapping particles being comparably susceptible for being negatively affected by photo-interaction on a decreased level of light beam intensity. Still further, it allows to provide equal trap stiffness for two lateral directions being arranged perpendicularly to an axis of light beam propagation independent of the polarization of the trapping laser.

When applying the optical trapping method according to the invention, during trapping of the optical trapping particle the optical trapping particle can be arranged in a medium having a third refractive index (η_{medium}), and the core particle of the optical trapping particle can be coated such that the second refractive index (η_{shell}) of the shell of the optical trapping particle is higher than or equals the third refractive index (η_{medium}) of the medium ($\eta_{shell} \geq \eta_{medium}$). The arrangement of the optical trapping particle in a medium while being trapped is commonly implemented in optical tweezers configurations. Thereby, the medium often is water or an aqueous solution. In such a configuration, it is particularly advantageous that the second refractive index (η_{shell}) is higher than or equals the third refractive index (η_{medium}) to achieve an optimized optical trapping.

Thereby, it can be preferred that the geometric mean of the first refractive index (η_{core}) of the core particle of the optical trapping particle and the third refractive index (η_{medium}) of the medium is higher than or equals the second refractive index (η_{shell}) of the shell of the optical trapping particle ($\eta_{\text{shell}} \leq \sqrt{\eta_{\text{medium}}\eta_{\text{core}}}$). Thus, for selecting a suitable shell material for coating a given core particle according to the inventive trapping method it is preferred that the refractive index (η_{shell}) of the shell matches anywhere in the range of $\eta_{medium} \leq \eta_{\text{shell}} \leq \sqrt{\eta_{\text{medium}}\eta_{\text{core}}}$. Like this, a comparably easy and efficient selection of a suitable shell material is possible.

When applying the optical trapping method according to the invention in a configuration where during trapping of the optical trapping particle the optical trapping particle is arranged in a medium having a third refractive index (η_{medium}), the core particle of the optical trapping particle can be coated such that the second refractive index (η_{shell}) of the shell of the optical trapping particle is about equal to the geometric mean of the first refractive index (η_{core}) of the core particle of the optical trapping particle and the third refractive index (η_{medium}) of the medium ($\eta_{\text{shell}} \approx \sqrt{\eta_{\text{medium}}\eta_{\text{core}}}$). Like this a more or less ideal arrangement of the second refractive index (η_{shell}) of the shell is easily possible. Thereby, the three refractive indices can additionally be in relation to each other as mentioned above, i.e. ($\eta_{core} \geq \eta_{shell} \geq \eta_{medium}$).

In an embodiment of the optical trapping method according to the invention a light beam, such as for example a laser beam, is induced by the optical tweezers while trapping the optical trapping particle, and the thickness (l) of the shell of the optical trapping particle is about equal to the quotient of the product of an integer (k) times two added by one and a wave length (λ) of the light beam, and the product of the second refractive index (η_{shell}) of the shell of the optical trapping particle and four. Accordingly, the thickness (l) of the shell is $l \approx \frac{(2k+1)\lambda}{4\eta_{shell}}$. With such an optical trapping method, a more or less ideal dimensioning of the thickness of the shell is easily possible. Thereby, the integer (k) can also be zero.

When applying the optical trapping method according to the invention in a configuration where during trapping of the optical trapping particle the optical trapping particle is arranged in a medium having a third refractive index (η_{medium}), and a light beam is induced by the optical tweezers while trapping the optical trapping particle, a diameter (d) of the core particle of the optical trapping particle can be chosen such that the diameter (d) is about equal to the quotient of a wave length (λ) of the light beam in vacuum and the third refractive index (η_{medium}) of the medium. Accordingly, the the diameter (d) of the optical trapping particle is $d \approx \frac{\lambda}{\eta_{medium}}$. With such an optical trapping method providing such a diameter of the core particle, the maximum trap stiffness can be improved such that at this core diameter trap stiffness of the coated optical trapping particle can be optimized, the axial displacement in respect to the light beam minimized, and back-focal plane detection properties optimized.

Thereby, the wave length of the light beam (λ) can be near to the wave length of infrared light (i.e. in the range of about 0.7 micrometer to 1.3 micrometer), and the medium can be water having a refractive index (η_{medium}) of about 1.33, such that the diameter (d) of the core particle of the optical trapping particle is greater than about 0.5 micrometer and less than about 1 micrometer.

Or, the wave length of the light beam (λ) can be near to the wave length of visible light (i.e. in the range of about 0.4 micrometer to 0.7 micrometer), and the medium can be water having a refractive index (η_{medium}) of about 1.33, such that the diameter (d) of the core particle of the optical trapping particle is greater than about 0.2 micrometer and less than about 0.6 micrometer.

This is particularly advantageous when the core particle is made of titanium dioxide (TiO_2). Here the diameter (d) of the core particle is greater than about 0.3 micrometer and less than about 0.6 micrometer for a wave length of the light beam in the near infrared light and the visible light spectrum.

The optical tweezers can comprise a lens for focussing a light beam, and the distance between the optical trapping particle and the focus of the light beam can be equal to or less than 0.5 micrometer while the optical trapping particle is trapped. Generally, the method according to the invention can minimize the distance between the optical trapping particle and the focus of the light beam which can improve trapping and detection properties. The distance can be minimized according to the invention by increasing the ratio of the gradient force to the scattering force. With such an optical trapping method internal reflections of the optical trapping particle can lead to destructive interference such that backscattering effects can be minimized.

Brief Description of the Drawings

The optical trapping particle according to the invention and the optical trapping method according to the invention are described in more detail hereinbelow by way of exemplary embodiments and with reference to the attached drawings, in which:

Fig. 1 shows a schematic cross sectional view of a optical trapping particle according to the invention;

Fig. 2 shows a schematic view of a trapping device for performing the trapping method according to the invention;

Fig. 3 shows a graph lateral trap stiffnesses of a first embodiment of an optical trapping particle according to the invention compared to other optical trapping particles;

Fig. 4 shows a graph of axial trap stiffnesses of the optical trapping particle from Fig. 3 compared to the other optical trapping particles; and

Fig. 5 shows a graph of escape forces of the optical trapping particle from Fig. 3 compared to the other optical trapping particles.

Mode(s) for Carrying Out the Invention

In Fig. 1 a schematic view of an optical trapping particle 1 is shown. The optical trapping particle 1 comprises a core particle 11 and a shell 12 wherein the core particle 11 is coated by the shell 12. In the embodiment shown in Fig. 1 the optical trapping particle 1 as well as the core particle have a spheric shape. The optical trapping particle 1 has an outer diameter D, the core particle 11 has a diameter d, and the shell 12 has a thickness l. The core particle 11 is made of a material having a first refractive index (η_{core}) and the shell is made of a material having a second refractive index (η_{shell}) wherein the first refractive index (η_{core}) is higher than the second refractive index (η_{shell}). The optical trapping particle 1 is always embodied in a medium with a third refractive index (η_{medium}) as described below.

In a first particular embodiment of the invention, the core particle 11 has a diameter d of 0.3 to 1.5 micrometer and is made of polystyrene (PS) having a first refractive index (η_{core}) of about 1.57. The shell 12 has a thickness l of 0.15 micrometer or more and is made of silica (SiO_x) having a second refractive index (η_{shell}) of about 1.44.

For coating the core particle 11 with the shell 12 according to this first embodiment , either positively charged, amine functionalized polystyrene core particles with a diameter of 913 nanometer ± 24 nanometer (e.g. manufactured by Polysciences, Warrington, USA) or nonfunctionalized 0.96 micrometer polystyrene core particles (e.g. manufactured by Bangs Laboratories, Fishers, USA) can be used. The core particles can firstly be cleaned in water, wherein only the non-functionalized core particles are treated with a 0.07 weight-% poly(allylamine hydrochloride) solution containing 0.36 mol NaCl. Both types of polystyrene core particles can then be coated with a monolayer of the amphiphilic, non-ionic polymer poly(vinylpyrrolidone) (e.g. PVP, manufactured by Sigma Aldrich) with an average molar mass of 360 kg/mol in an ethanol solution. To the ethanol solution containing the stabilized particles, an ammonia solution and subsequently a certain volume of tetraethoxysilane solution (0.1 mol) can then be added in a stepwise manner while stirring. The concentration, volume, and number of steps (≤5) can thereby determine the final coating thickness. The products can be separated from secondary nucleation by centrifugation. Such a procedure can be robust to produce silica layers of up to at least
350 nanometer thickness.

In a second particular embodiment of the invention, the core particle 11 has a diameter d of 0.3 to 1.5 micrometer and is made of polystyrene (PS) having a first refractive index (η_{core}) of about 1.57. The shell 12 has a thickness l of 0.15 micrometer or more and is made of polytetrafluoroethylene (PTFE) having a second refractive index (η_{shell}) of about 1.32.

In a third particular embodiment of the invention, the core particle 11 has a diameter d of 0.1 to 1.5 micrometer and is made of titanium dioxide (TiO_2) having a first refractive index (η_{core}) of about 2.4. The shell 12 has a thickness l of 0.06 micrometer or more and is made of polystyrene (PS) having a second refractive index (η_{shell}) of about 1.57.

Fig. 2 schematically shows an optical trapping device such as in particular an optical tweezers. The optical tweezers comprises a light source 2 and an optical lens 4. In operation the light source 2 emits a light beam, i.e. a laser beam 3, through the optical lens 4. The optical lens 4 focuses the laser beam 3 into a spot 30 such that an optical trap is generated at the spot 30. At least in the area around the spot 30 a medium 5 is arranged having a third refractive index (η_{medium}). By locating the optical trapping particle 1 at the spot 30, the optical force of the focused laser beam 3 acts on the optical trapping particle 1 such that it is trapped by the optical tweezers.

The optical trapping device from Fig. 2 can for example be set up as described in Schäffer, E., Nørrelykke, S. F., and Howard, J.; "Surface forces and drag coefficients of microspheres near a plane surface measured with optical tweezers"; Langmuir 23, 3654 - 3665 (2007) which is enclosed by reference, or in Bormuth, V., Howard, J., and Schäffer, E.; "LED illumination for video-enhanced DIC imaging of single microtubules"; J. Microsc; 226, 1 - 5 (2007) which is enclosed by reference. To these set-ups a Faraday isolator (e.g. IO-3-1064-VHP, Optics for Research, Caldwell, USA) can be added directly after the laser head and before the first beam expander. Briefly, a 1.5 Watt Nd:YVO_4 laser (having a wave length of 1064 nanometer, a M2-value of about 1.25 (e.g. manufactured by Smart Laser Systems, Berlin, Germany) can be expanded to a beam waist of about 3 millimeter and coupled into an inverted microscope. The trapping objective can be a Zeiss Plan-Neo Neofluar 100, 1.3 NA, oil-immersion objective with a back aperture of about 6 millimeter. A position-sensitive photodiode for back-focal-plane detection in three dimensions can be used.

As an example, graphs of trapping properties of the first embodiment of the optical trapping particle 1 according to the invention having a core particle 11 made of polystyrene (PS) and a shell made of silica (SiO_x) are shown in Fig. 3, Fig. 4, and Fig. 5 for illustration purposes. Thereby, these trapping properties are displayed in the graphs in comparison to the corresponding trapping properties of uncoated uniform optical trapping particles made of polystyrene (PS) and of silica (SiO_x), respectively. An optical trapping device corresponding to the optical trapping device described above is used in this example wherein the laser beam 3 has a wave length of 1064 nanometer in vacuum, the medium is an aqueous solution, and the wave length of the laser beam 3 in the medium is 800 nanometer.

In the mentioned graphs, Mie functions 8 of the first embodiment of the optical trapping particle 1 according to the invention and several corresponding discrete measurements 81 of the first embodiment of the optical trapping particle 1 according to the invention are shown in Fig. 3, Fig. 4, and Fig. 5. The examined optical trapping particles 1 according to the invention have core particles 11 with two different diameters d: For optical trapping particles 1 having an outer diameter D of 1.5 micrometer or less, the core diameter is 913 nanometer and for optical trapping particles 1 having an outer diameter D of more than 1.5 micrometer the core size is 960 nanometer. The data points marked with ∞ are measured in a 80% by weight glycerol solution having a refractive index matching the refractive index of the shell 12. The measurements 61, 71, and 81 are averages of at least six measurements for each type of optical trapping particle. Errors are standard deviations and are plotted if they are larger than the measurement itself. The laser intensity in the spot 30 of the laser beam 3 is 0.21 Watt in the graphs shown in Fig. 3 and Fig. 4 and 0.07 Watt in the graph shown in Fig. 5.

Further, a corresponding Mie function 6 of uncoated uniform optical trapping particles made of polystyrene (PS), a corresponding Mie function 7 of uncoated uniform optical trapping particles made of silica (SiO_x), several discrete measurements 61 of the optical trapping particles made of polystyrene (PS), and several discrete measurements 71 of the optical trapping particle made of silica (SiO_x) are shown in Fig. 3, Fig. 4, and Fig. 5.

The graph of Fig. 3 shows a lateral trap stiffness in piconewton per nanometer as in relation to the outer diameter of the mentioned three types of optical trapping particles in micrometer. Lateral in this context relates to a direction essentially perpendicular to the direction of propagation of the laser beam 3. The graph of Fig. 4 shows an axial trap stiffness in piconewton per nanometer in relation to the outer diameter of the mentioned optical trapping particles in micrometer. Axial in this context relates to the direction of propagation of the laser beam 3. The graph of Fig. 5 shows an escape force in piconewton in relation to the outer diameter of the mentioned optical trapping particles in micrometer.

As can be seen in Fig. 3 and in Fig. 4, the lateral trap stiffness of the optical trapping particle 1 according to the invention as well as the axial trap stiffness of the optical trapping particle 1 according to the invention are increasingly higher with increasing outer diameter of the optical trapping particles compared to the lateral trap stiffness of the optical trapping particle made of polystyrene (PS) and the optical trapping particle made of silica (SiO_x), respectively. This is particularly significant for optical trapping particles having an outer diameter greater than the wavelength of the laser beam 3 in the medium 5. All measurements 61, 71, 81 agree quantitatively with the Mie scattering calculations.

Other alternative embodiments of the optical trapping particle according to the invention and the optical trapping method according to the invention are conceivable with any combination of features from different according embodiments described above. For example, explicitly mentioned in this context is that the core particle as well as the optical trapping particles can have any other shape than a spheric shape. In particular, the core particle can be ellipsoid and the shell can be ellipsoid resulting in an overall ellipsoid shape. Or the core particle can be ellipsoid and the shell compensates ellipticity such that the over all shape of the optical trapping particle is spheric.

Claims

1. Optical trapping particle (1), characterized in that the optical trapping particle (1) comprises a core particle (11) having a first refractive index and a shell (12) having a second refractive index wherein the first refractive index is higher than the second refractive index.

2. The optical trapping particle (1) of claim 1, wherein the optical trapping particle is a optical trapping particle suitable for optical trapping by means of an optical tweezers.

3. The optical trapping particle (1) of claim 1 or 2, wherein a diameter (d) of the core particle (11) is greater than about 0.1 micrometer and less than about 2 micrometer.

4. The optical trapping particle (1) of claim 3, wherein the diameter (d) of the core particle (11) is greater than about 0.3 micrometer.

5. The optical trapping particle (1) of claim 3 or 4, wherein the diameter (d) of the core particle (11) is less than about 1.5 micrometer.

6. The optical trapping particle (1) of any one of claims 1 to 5, wherein an outer diameter (D) of the optical trapping particle is less than about 10 micrometer.

7. The optical trapping particle (1) of claim 6, wherein the outer diameter (D) of the optical trapping particle is less than about 3 micrometer.

8. The optical trapping particle (1) of any one of claims 1 to 7, wherein a thickness (l) of the shell (12) is greater than or equals about 0.06 micrometer.

9. The optical trapping particle (1) of claim 8, wherein the thickness (l) of the shell (12) is greater than or equals about 0.1 micrometer.

10. The optical trapping particle (1) of any one of claims 1 to 9, wherein the core particle (11) is made of polystyrene, titanium dioxide, diamond, zinc sulphide, vaterite, calcite, lysozyme crystals, quartz, or polymethylmethacrylate.

11. The optical trapping particle (1) of any one of claims 1 to 10, wherein the shell (12) is made of polytetrafluoroethylene, polystyrene, silica, or polymethylmethacrylate.

12. The optical trapping particle (1) of any one of claims 1 to 11, wherein the core particle (11) has a non-spherical shape.

13. The optical trapping particle (1) of any one of claims 1 to 12, wherein the core particle (11) is made of a birefringent material.

14. The optical trapping particle (1) of any one of claims 1 to 13, wherein the core particle (11) is an optical trapping particle (1) according to any one of claims 1 to 12.

15. Optical trapping method comprising the step of trapping a particle by means of an optical tweezers, characterized in the step of coating a core particle (11) with a shell (12) such that the particle being trapped by means of the optical tweezers is an optical trapping particle (1) according to any one of claims 1 to 14.

16. The optical trapping method of claim 15, wherein during trapping of the optical trapping particle (1) the optical trapping particle (1) is arranged in a medium having a third refractive index, and the core particle (11) of the optical trapping particle (1) is coated such that the second refractive index of the shell (12) of the optical trapping particle (1) is higher than or equals the third refractive index of the medium.

17. The optical trapping method of claim 16, wherein the geometric mean of the first refractive index of the core particle (11) of the optical trapping particle (1) and the third refractive index of the medium is higher than or equals the second refractive index of the shell (12) of the optical trapping particle.

18. The optical trapping method of claim 15, wherein during trapping of the optical trapping particle (1) the optical trapping particle (1) is arranged in a medium having a third refractive index, and the core particle (11) of the optical trapping particle (1) is coated such that the second refractive index of the shell (12) of the optical trapping particle (1) is about equal to the geometric mean of the first refractive index of the core particle (11) of the optical trapping particle (1) and the third refractive index of the medium.

19. The optical trapping method of any one of claims 15 to 18, wherein a light beam (3) is induced by the optical tweezers while trapping the optical trapping particle, and the shell (12) coating the core particle (11) of the optical trapping particle (1) has a thickness (l) which is about equal to the quotient of the product of an integer times two added by one and a wave length of the light beam, and the product of the second refractive index of the shell (12) of the optical trapping particle (1) and four.

20. The optical trapping method of any one of claims 15 to 19, wherein during trapping of the optical trapping particle (1) the optical trapping particle (1) is arranged in a medium having a third refractive index, a light beam (3) is induced by the optical tweezers while trapping the optical trapping particle, and a diameter (d) of the core particle (11) of the optical trapping particle (1) is chosen such that the diameter (d) is about equal to the quotient of a wave length of the light beam (3) in vacuum and the third refractive index of the medium.

21. The optical trapping method of claim 20, wherein the wave length of the light beam (3) is near to the wave length of infrared light, the medium is water, and the diameter (d) of the core particle (11) of the optical trapping particle (1) is greater than about 0.5 micrometer and less than about 1 micrometer.

22. The optical trapping method of claim 20, wherein the wave length of the light beam (3) is near to the wave length of visible light, the medium is water, and the diameter (d) of the core particle (11) of the optical trapping particle (1) is greater than about 0.2 micrometer and less than about 0.6 micrometer.

23. The optical trapping method of any one of claims 15 to 22, wherein the optical tweezers comprises a lens (4) for focussing a light beam, and the distance between the optical trapping particle (1) and the focus of the light beam (3) is equal to or less than 0.5 micrometer while the optical trapping particle (1) is trapped.

24. Optical trapping particle (1), wherein the optical trapping particle (1) comprises a core particle (11) and a shell (12).

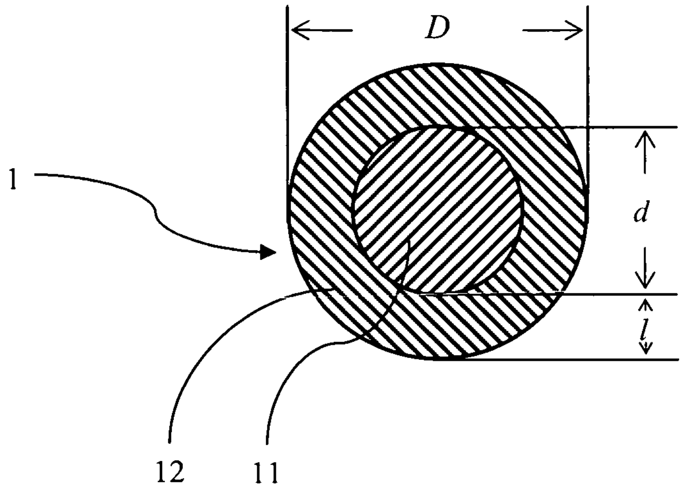

Fig. 1

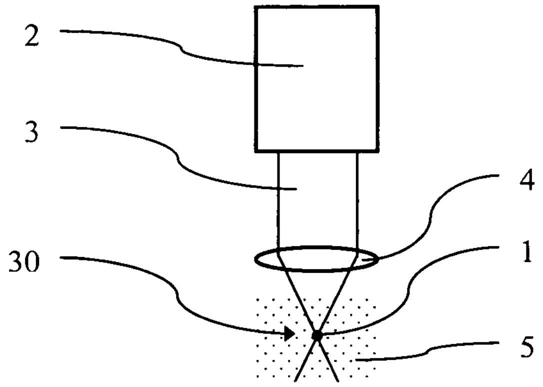

Fig. 2

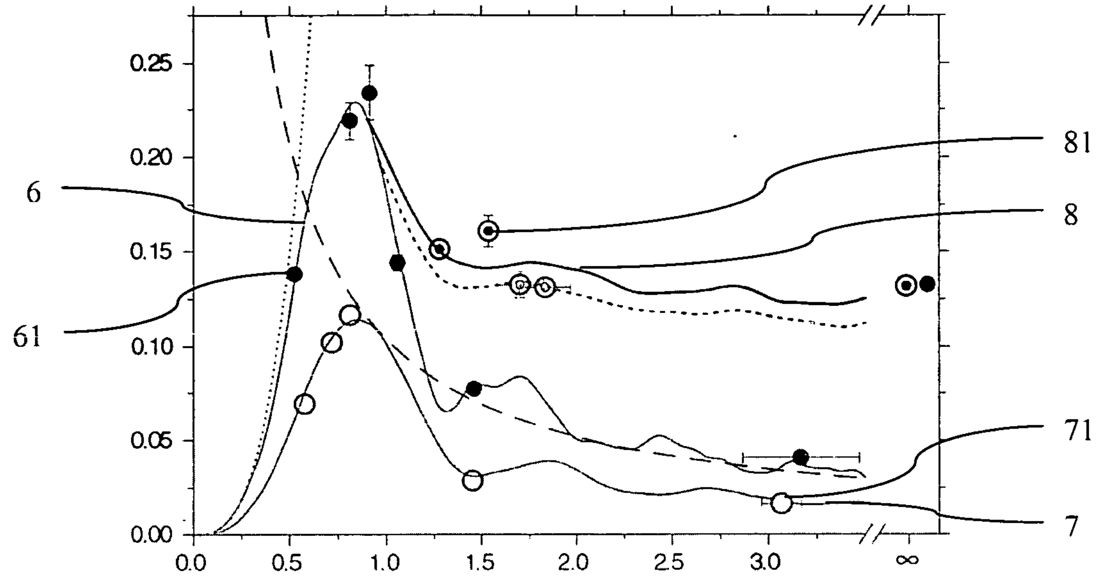

Fig. 3

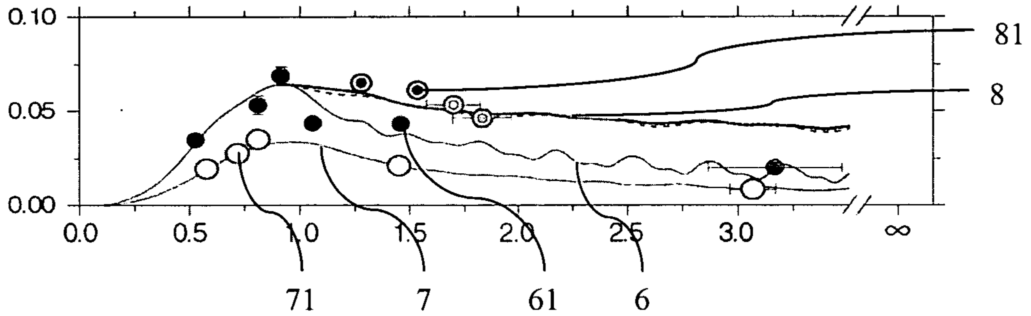

Fig. 4

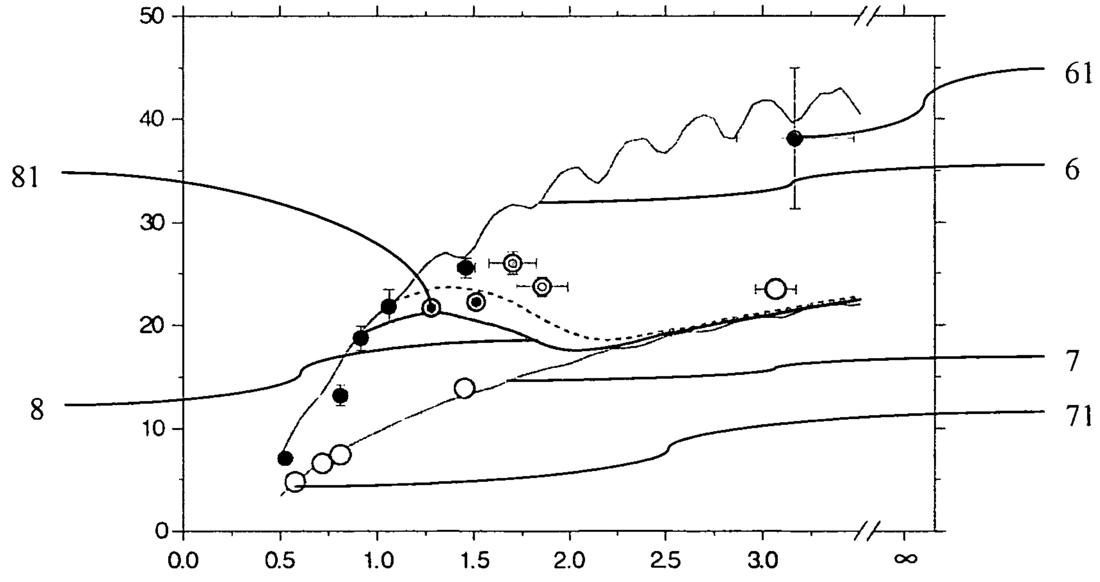

Fig. 5