Appl. Phys. B 71, 801–805 (2000) / Digital Object Identifier (DOI) 10.1007/s003400000424

Applied Physics B
Lasers
and Optics

Laser-induced hybrid trap for micro-bubbles

B.L. Lü, Y.Q. Li, H. Ni, Y.Z. Wang*

Joint Laboratory for Quantum Optics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, P.O. Box 800-211, Shanghai 201800, China
(Fax: +86-21/59528812)

Received: 3 February 2000/Revised version: 6 July 2000/Published online: 8 November 2000 –

Abstract. Micro-bubbles have been stably trapped in liquid ethanol by a focused argon laser beam. Two equilibrium points where bubbles can be trapped are observed to be at the center and the rim of the laser beam. The light force is also able to push a bubble into the liquid to a position well below the liquid surface. Both the light-pressure force and the fluid force induced by the convection of the liquid medium are calculated. The results clearly show that these two kinds of forces account for the formation of trapping potential.

PACS: 42.50.Vk; 36.40.Vz; 32.80.Pj

The optical trapping and manipulation of micro-particles has been an interesting research subject in the last 30 years. Ashkin used a laser beam to trap and levitate micro-particles [1]. Chu also controlled bacteria and DNA using the same technique [2]. Recently, trapping of nanoparticles and micro-particles [3] was realized by a Gaussian standing wave. In all these experiments, the particles have larger refractive indices than the surrounding media to achieve a transverse radiation force that draws the particle in to the beam axis [1, 4], as shown in Fig. 1. In contrast, if one reverses the relative magnitudes of the indices of the media, the sign of the transverse light-pressure force reverses, and the particle should be pushed out of the beam. This condition is certainly true in an extreme case of a low-index particle in a high-index medium, namely, an air bubble. So a Gaussian beam is unable to trap a gas bubble by its light-pressure force alone, but some other techniques such as negative dielectro-phoresis were once used for the manipulation of bubbles.

In this paper we report the observation of stable trapping of micro-bubbles in liquid ethanol using an argon laser beam. A micro-bubble floating on the liquid surface is able to be trapped by a Gaussian beam passing vertically through the medium. A laser beam directed downwards can also push a micro-bubble deep into the liquid while trapping it in transverse direction. A theoretical model takes the fluid force of the ethanol medium as well as the light-pressure force into consideration, and confirms that these two forces together rather than the light force alone trap the micro-bubbles. This hybrid trap is a new technique of manipulating micro-bubbles.

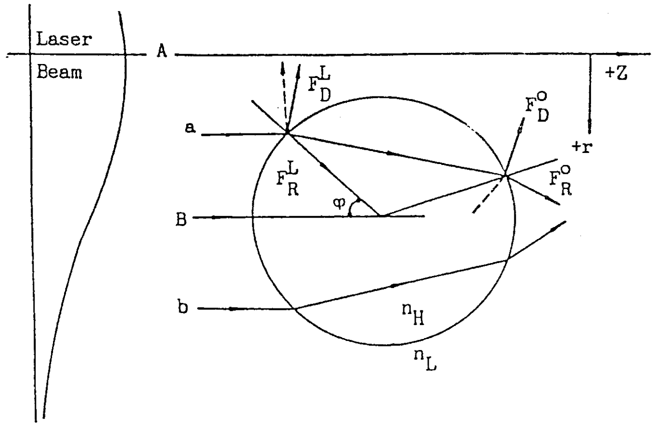


Fig. 1. Light-pressure force exerted on a micro-particle of high index in a low-index medium ($n_H > n_L$). F_R and F_D represent the forces resulting from the momentum variation of the light rays when they are reflected and refracted, respectively. If the relative magnitude of the indices of the media is reversed, i.e., $n_H < n_L$, as in the case of a micro-bubble, the sign of the radial deflection forces reverses

1 Principle of hybrid trap

Consider a micro-bubble submerged in liquid medium of ethanol. When it is illuminated by a Gaussian beam in the vertical direction, the reflection and refraction of the light rays will produce forces on the micro-bubble, as shown in Fig. 1. The transverse component of the light-pressure force tends to push the micro-bubble out of the beam while the axial force pushes it along the beam. Both the transverse and axial light forces can be calculated with a geometrical optics approach [5] provided that the micro-bubble's size is much larger than the wavelength of the light. We find the transverse

*Corresponding author.

force F_x and the axial force F_z are given by

$$F_x = \int \mathrm{d}\theta \int \mathrm{d}\phi (s/c) \left(R \sin 2\theta + \sum_n T^2 R^{n-1} \sin \theta_n \right) \times R_\mathrm{b}^2 \sin\theta \cos\theta \cos\phi \,, \quad (1)$$

$$F_z = \int \mathrm{d}\theta \int \mathrm{d}\phi (s/c) \left(1 + R \cos 2\theta + \sum_n T^2 R^{n-1} cos\theta_n \right) \times R_\mathrm{b}^2 \sin\theta \cos\theta \sin\phi \,. \quad (2)$$

Here R_b is the radius of the micro-bubble, s is the scalar length of the Poynting vector, c is the speed of light, θ represents the zenithal angle, θ_n is defined as $2\theta + n[\pi - 2\sin^{-1}(n \sin\theta)]$,$R$ and T are the reflective and refractive coefficients on the interface of micro-bubble, respectively. Both R and T can be calculated directly using the Fresnel formula. Figure 2a displays a theoretical curve of transverse force F_x on a micro-bubble of ~20-μm diameter illuminated by a 1-W argon laser of 514.5 nm. In the calculation, the liquid medium is assumed to be ethanol as in the case of our experiment. F_x is a kind of centrifugal force, and hence takes negative values here. The axial force F_z upon the same micro-bubble is shown in Fig. 2b. The appearance of a negative sign in F_z means a downwards direction $(-z)$ which the laser beam is assumed to take. If the direction of the laser beam is reversed, going upwards, F_z will have positive values.

On the other hand, the liquid medium is not thoroughly transparent to the laser beam. The slight absorption of the laser beam will heat the medium, and consequently a temperature field is formed inside the medium. Then convection of the liquid is caused by the non-uniformity of the temperature distribution. Since the heat source is in the region of the laser beam, the fluid field corresponding to the convection of the liquid medium is symmetric with the beam axis and like a micro-fountain, as shown in Fig. 3. To calculate the fluid force on the micro-bubble, one needs to know the velocity distribution of the fluid at first. The relation between temperature gradient ∇T and fluid velocity v may be written as [7]

$$\nabla(v^2/2) = gz\beta\nabla T \,, \quad (3)$$

where g is the acceleration due to gravity and β represents the volume thermal expansion coefficient. Both the convection and heat conduction occur in the liquid medium. The equation of energy change for the liquid takes the following form [7]:

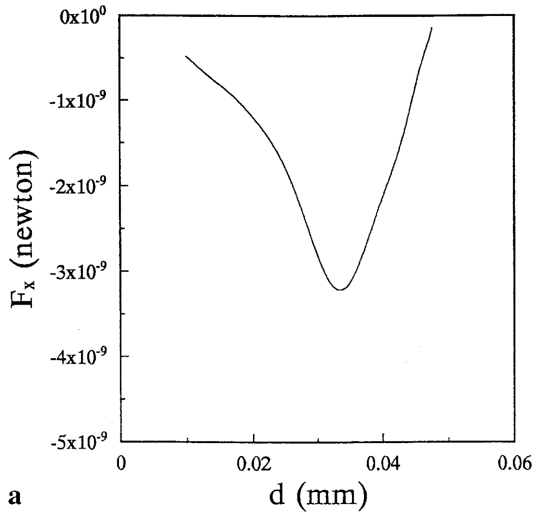
$$\frac{\partial}{\partial t}(e + v^2/2) + (\boldsymbol{v} \cdot \nabla)(e + v^2) = \boldsymbol{g} \cdot \boldsymbol{v} + \frac{1}{\varrho}\nabla(\boldsymbol{g} \cdot \boldsymbol{v}) + \alpha + \frac{1}{\varrho}\nabla \cdot (\lambda \nabla T) \,. \quad (4)$$

Here e is the internal energy, α is the absorption coefficient, $\boldsymbol{p}$ represents the stress tensor of the medium and λ is the heat conductivity. The first term on the left-hand side describes the energy variation, the second is the energy transfer due to the convection. The first and second terms on the right-hand side are work done by gravity and surface force, respectively. The third one is the absorbed radiation energy, and the fourth represents the heat energy conducted through the limit surface. Furthermore, the continuity of the liquid is normally expressed as [7]:

$$\frac{1}{\varrho}\frac{\partial \varrho}{\partial t} + \nabla \cdot \boldsymbol{v} = 0 \,. \quad (5)$$

The equation group consisting of the above three relations is adequate for the calculation of the fluid velocity distributions under some proper approximations. For simplicity, the heat source has been assumed to be a line coinciding with the axis of the laser beam. The tedious computing job was implemented by running a computer program.

It is pretty difficult to calculate the fluid force on the micro-bubble since the liquid medium is not an ideal fluid for a bubble with such a large size (~20 μm). In order to get a qualitative physical picture, the Bernoulli's theorem was



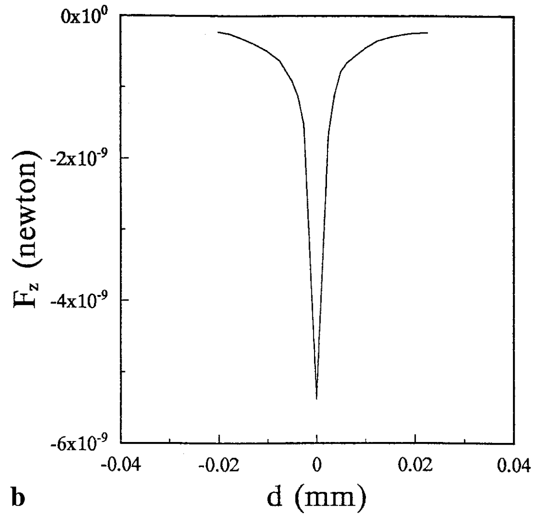


Fig. 2. a The calculated transverse component of light-pressure force on a 20-μm-diameter bubble. The laser beam is directed downwards to pass through the glass cell with liquid ethanol inside. The d represents the distance from the beam axis to the center of bubble. The negative sign of F_x values indicates centrifugal direction. The laser power is $P = 1$ W, beam diameter is ~ 20 μm. **b** The calculated axial force of light pressure on a bubble. All parameters used are the same as in Fig. 2a. The negative sign of the light force F_z represents the downwards direction since the laser beam is assumed to be directed in this way as in one case of our experiment

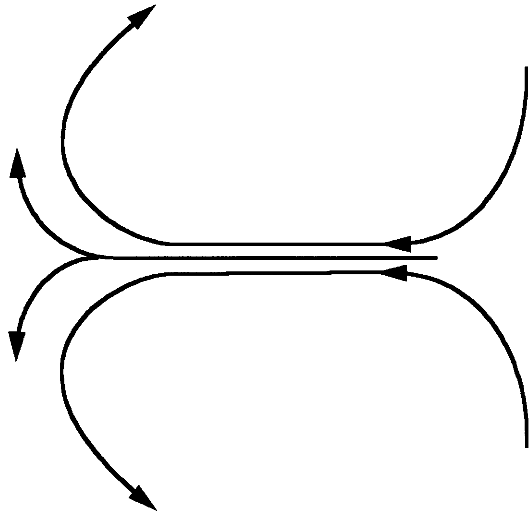


Fig. 3. Schematic diagram of the fountain-like fluid caused by the convection of the ethanol that gets heated due to the absorption of the laser beam passing through the glass cell vertically. The symmetry axis of the fluid field coincides with the laser beam axis

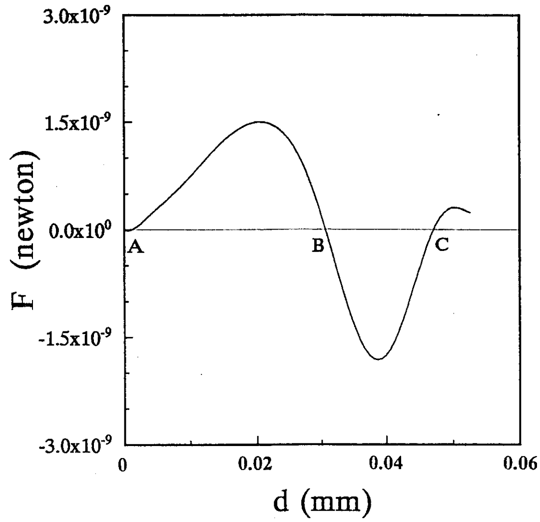


Fig. 5. The net transverse force calculated from the superposition of the transverse light-pressure force and fluid force shown in Fig. 2a and Fig 4, respectively. A, B and C are the three equilibrium points, but only A and C are stable for the trapping of a bubble

used in the derivation of the transverse fluid force F'_x. We find

$$F'_x = -R_b^2 \int\int \frac{1}{2}\varrho^2 \nu^2 \sin^2\theta \cos\phi \,d\theta\, d\phi\,, \qquad (6)$$

where ϱ is the density of the medium, ν is the fluid velocity on the surface of the micro-bubble. For the micro-bubble in the case of Fig. 2, the theoretical result of transverse fluid forces is displayed in Fig. 4. In contrast with the transverse light-pressure force, the transverse fluid force is centripetal and tends to draw the micro-bubble in to the light beam. The two transverse forces, added together, produce a total transverse force F as shown in Fig. 5. When the micro-bubble moves away from the beam axis, F will change signs. A, B and C are three equilibrium points of the micro-bubble. However, B is an unstable point. Only A and C, located at the axis and rim of the laser, respectively, are two stable equilibrium points where the micro-bubble can be trapped. In other words, the joining of the fluid force makes it possible to trap a micro-bubble either in the center or in the rim of the laser beam. In addition, the active range of the fluid is hundreds of times wider than the transverse size of the laser beam. So a micro-bubble, which initially stays far away from the beam axis, is, therefore, able to be dragged to the laser beam.

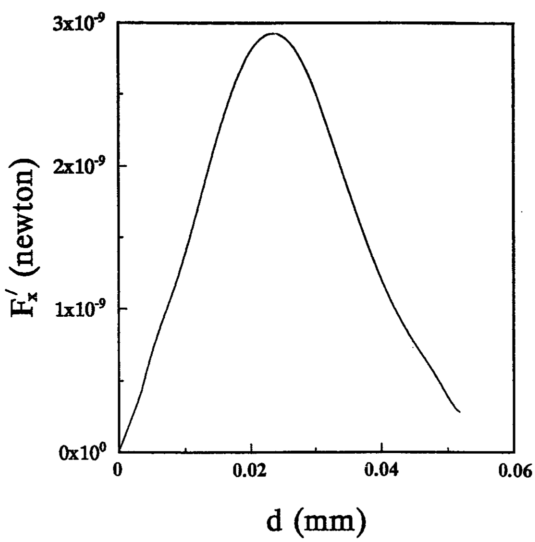


Fig. 4. Theoretical curve of the transverse fluid force on a ~20-μm-diameter bubble versus the distance between the beam axis and the center of the bubble. The calculations were carried under the same conditions as in Fig. 2 to facilitate comparison. The positive sign of F'_x values represents the centripetal direction of the transverse force

As the laser beam goes upwards through the medium, the micro-bubble will float on the liquid surface while trapped in the transverse direction, because the buoyancy force, the axial light-pressure force and the axial fluid force point upwards. However, as the direction of the laser beam is reversed, the axial light-pressure force points downwards, and it is pretty large for a micro-bubble at the axis of the laser beam (see Fig. 2b). One can expect that the axial light-pressure force is able to overcome the buoyancy force and the axial fluid force, pushing the micro-bubble into the medium to a stable point where these three forces reach equilibrium.

2 Experimental setup

The experimental arrangement is as shown in Fig. 6. An argon laser of $\lambda = 514.5$ nm is focused into a glass cell by lens L1 (or M1) with 3-cm focal length. The glass cell with a thickness of 1 cm is loaded with some pure ethanol liquid of ~8 mm thickness. The Gaussian laser beam with a beam waist ~10 μm can be directed either upwards by lens L1 or downwards by lens M1. The glass cell is mounted on a two-axis translator, so it can be moved in the horizontal plane. The lens L1 can be moved up and down to change the focus position of the light. Tens of Nd-doped glass micro-spheres are placed on the bottom plate of the glass cell. When a glass micro-sphere is illuminated by the focused laser beam, it absorbs the laser energy and is heated to make the surrounding liquid ethanol vaporize, then a gas bubble is formed. The sizes

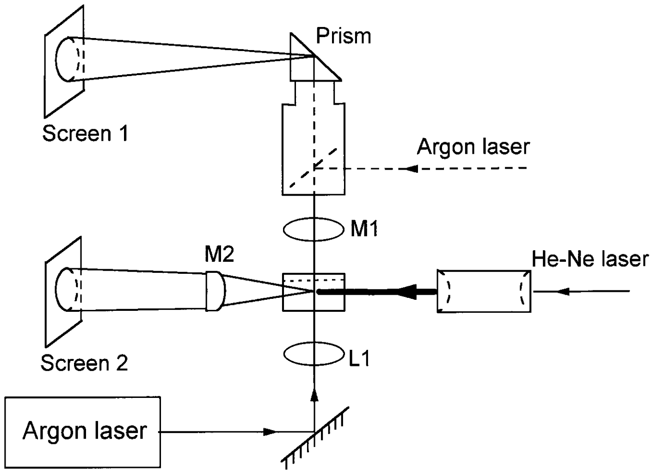


Fig. 6. Experimental setup. An argon laser beam is focused into the glass cell and passes through the liquid ethanol. Some Nd-glass micro-spheres that act as absorbents are placed at the bottom of the cell

of bubbles range from $\sim 10\,\mu$m to hundreds of μm, depending on the intensity and illumination time of the laser beam. The position and movement of the studied bubble are monitored using an imaging system. An auxiliary laser beam of $\lambda = 632.8$ nm enters the medium, acting as the light source for the imaging of a bubble in case the bubble is far off the argon laser beam. The bubble is then imaged on the screen 2 through the lens M2, and its vertical position is thus monitored. When a bubble lies in the region of the argon laser beam, it can also be imaged on the screen 1 for monitoring its transverse position. A video recorder was used to record the pictures on the two screens. The fluid velocity can also be estimated by measuring the speed of micro-sized irregular glass particles that are brought to the fluid region. In our experiment, the velocity at the center of the fluid field is about $v_0 \approx 3$ mm/s along the axis.

3 Results and discussion

For a gas bubble floating on the liquid surface, one can make it close to the laser beam by slowly moving the glass cell. When the beam focus is adjusted a little above the bubble and the diameter of the bubble is smaller than the beam spot, the bubble is likely to be trapped at the rim of the beam, as shown in Fig. 7a. The trapped bubble does not leave the beam even if the glass cell is moving in the horizontal plane. Apparently, this stable trap position corresponds to point C in Fig. 5. It is also observed that a bubble can be trapped at the center of the laser beam if the laser beam focus is very close to the bubble. Figure 7b shows a typical case of this kind of trap which is predicted by our calculation in Fig. 5. The stable equilibrium point A in Fig. 5 is just the position where the bubble stays. However, the bubble trapped at the center of the beam undergoes a small damping oscillation with a 2-s damping time due to the resistance of the liquid. In the experiment, bubbles grow near the absorbent region where the temperature is considerably higher than that of the liquid. When trapped in the ethanol by the laser beam, the bubble will become cool and shrink gradually. While the bubble is getting smaller and smaller towards a specific size, it undergoes a violent oscillating movement although no change occurs for the fluid field. It seems as if the stable point becomes unstable and the resistance to the bubble drops abruptly. This phenomenon can not be explained using the above theoretical model.

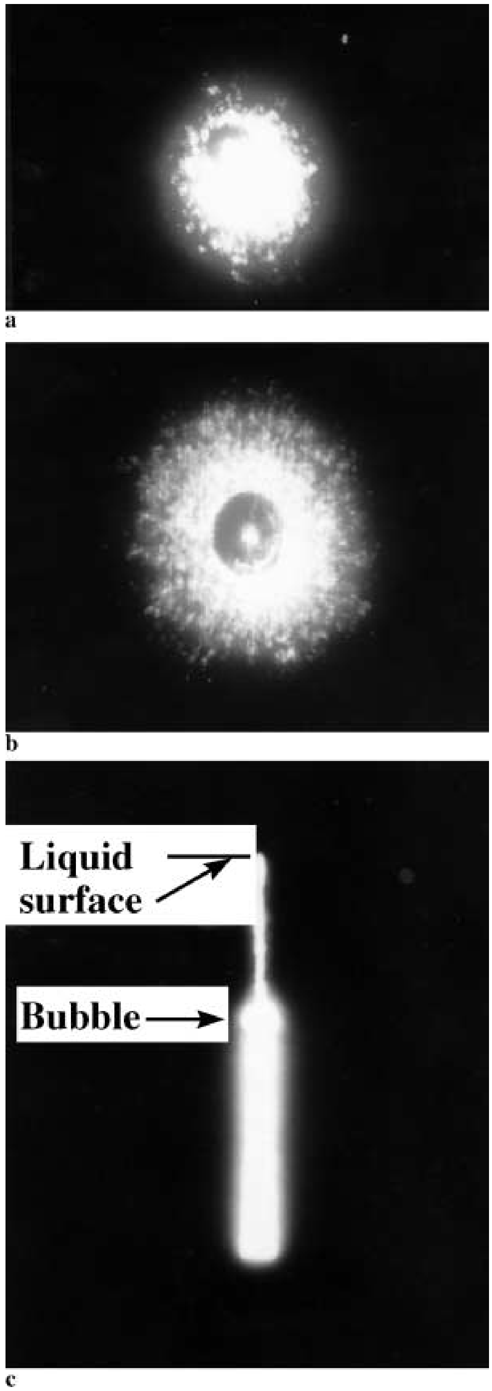


Fig. 7a–c. Trapped micro-bubbles. **a** Trapped near the rim of the laser beam. **b** Trapped at the center of the laser beam. **c** A bubble that is pushed down to a position well below the liquid surface

When the laser beam is directed downwards and focused on a bubble, it pushes the bubble into the liquid while trapping the bubble at the beam center. As shown in Fig. 7c, a bubble is trapped in a point $1 \sim 2$ mm below the liquid surface. Moving the focus up and down would force the trapped bubble to follow the focus. The result clearly shows that the light-pressure force can indeed be strong enough to overcome the buoyancy force and the fluid force. This opens a new way to manipulate a bubble in a liquid without mechanical contact.

4 Conclusion

As a liquid medium has a weak absorption of the laser beam, there is always combined action of light-pressure force and fluid force when trapping and manipulating micro-particles in a liquid medium. Thus it is necessary to study the character of the hybrid trap induced by the laser. Our paper investigates the hybrid trap in both theory and experiment. This kind of trap is used to control the gas bubble in liquid. The light-pressure force also pushes a gas bubble into the liquid medium. These observations qualitatively agree with our theoretical calculation. The hybrid trap is a potential new technique to manipulate a gas bubble.

Acknowledgements. We thank Professor Y.R. Shen for his comments. Thanks also go to Professor G.Y. Wang, Professor Y.G. Xu and Mr. W.D. Shao for their cooperation in this experiment. This work was supported by the National Nature Science Foundation of China under the grant no. 19 834 060 and the Ministry of Science and Technique of China under grant no. 95-YU-34. The authors gratefully acknowledges the support of K.C. Wong Education Foundation, Hong Kong.

References

1. A. Ashkin, J.M. Dziedzic: Phys. Rev. Lett. **38**, 1351 (1977); Appl. Opt. **20**, 1803 (1981)
2. S. Chu: “Optical Manipulation of DNA”, XVII International Quantum Electronic Conference, 21–25 May 1990, Anaheim, USA, QWJS paper
3. P. Zemanek, A. Jones, L. Sramek, M. Liska: Opt. Lett. **24**, 1448 (1999)
4. Y.R. Shen: *The Principles of Nonlinear Optics* (Wiley, New York 1984)
5. G. Roosen: Can. J. Phys. **57**, 1260 (1979)
6. L.M. Milne-Thompson: *Theoretical Hydro-dynamics*, 4th edn. (Macmillan, New York 1960) Art. 6. 22
7. J.R. Chen: *Hydrodynamics and Heat Transfer*, 1st edn. (Defence Industrial Press, China 1984) 15034. 2760