# Improvement of the axial trapping effect using azimuthally polarised trapping beam*

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A dual optical tweezers system, which consists of a doughnut mode optical tweezer (DMOT) with the azimuthally polarised trapping beam and a solid mode optical tweezer (SMOT) with the Gauss trapping beam was constructed to compare the axial trapping effect of DMOT and SMOT. The long-distance axial trapping of ST68 microbubbles (MBs) achieved by DMOT was more stable than that of SMOT. Moreover the axial trapping force measured using the viscous drag method, was depended on the diameter of the particle, the laser power, and the numerical aperture (NA) of the objective lens. The measurement of the axial trapping force and the acquisition of CCD images of trapping effect confirmed that the DMOT showed excellent axial trapping ability than SMOT. A simple and effective method is developed to improve axial trapping effect using the azimuthally polarized beam as trapping beam. This is helpful for the long-distance manipulating of particles especially polarised biological objects in axial direction.

**Keywords:** optical tweezers, azimuthally polarised beam, axial trapping force, ST68 microbubbles
**PACC:** 9430H, 4225J, 4215E

## 1. Introduction

Optical trapping, invented by Ashkin *et al.*[1] in 1986, has been developed rapidly because of its growing applications in physics, chemistry, and biology.[2−5] When the interaction of a focused laser beam with a small particle is considered two different forces, gradient force and scattering force, are of key importance. The scattering force which originates from the reflection of the trapping beam overcomes the gradient force exerted on the particle and pushes the particle out of the trap, especially in the propagation direction. Recently, most of the studies are performed along the beam axis, especially for single-molecule experiments.[6] However, axial trapping efficiency is weaker than the radial counterpart under normal circumstances. Therefore, how to improve the axial trapping efficiency has became a key concern that must be addressed in the field of optical tweezers technology. The scattering force results from reflection while the reflectivity depends on the laser polarisation.[7] As such, choosing the appropriate polarisation pattern is required to improve the axial trapping effect. As one type of cylindrical-vector beams, the azimuthally polarised beam which does not have uniformly polarised pattern in the usual sense,[8−10] can meet the requirement to improve the axial trapping efficiency. More interestingly, azimuthally polarised beam could form a doughnut intensity distribution after being tightly focused.[11,12] Due to their polarisation singularity, the azimuthally polarised beam can further broaden the application fields of optical tweezers when it is used as trapping beam. However, previous reports only discuss the results of theoretical research of involving azimuthally polarised laser beam,[13−15] and the experimental research on manipulating particles with azimuthally polarised trapping beam is rarely reported.

In this letter, a dual optical tweezers system, which consists of a doughnut mode optical tweezers (DMOT) and a solid mode optical tweezers (SMOT), was constructed to compare the axial trapping effects of DMOT and SMOT. In this system, DMOT was realised using azimuthally polarised beam as trapping beam. The axial trapping force, which depended on the diameter of ST68 microbubbles (MBs), the laser power, and the NA of the objective lens, was measured. The measurement of the axial trapping force and the acquisition of CCD images of axial trapping effect confirmed that the axial trapping ability of DMOT was better than that of SMOT. We described a simple and effective method to improve axial trapping effect using the azimuthally polarised beam as

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trapping beam.

## 2. Experimental set-up and material

A dual optical tweezers system, shown in Fig. 1, consists of a DMOT with the azimuthally polarised beam as trapping beam (Fig. 1(a)) and a SMOT with the linearly polarised Gauss beam as trapping beam (Fig. 1(b)). The lasers used in the DMOT and SMOT are the same type of semiconductor laser, working at 650 nm. And the two optical tweezers can manipulate particles independently. The azimuthally polarised beam is formed by the liquid-crystal polarisation converter (LPC, APCoptix Switzerland) which consists of a variable phase shifter (VPS), a polarisation rotator (PR) and a $\theta$-cell. The laser beam is tightly focused to a spot by 40× (NA=0.65) or 100× (NA=1.25 oil immersion) objective lenses to form a stable 3D trap. The sample chamber made of a cover-glass and a slide-glass is used to seal a drop of sample solution. The attenuation of the microscope is about 30% for the 100× objective and 15% for the 40× one. In our experiment the laser power is measured after the objective lens, and varied in the range between 1 and 70 mW. The magnified image is observed with a CCD camera.

The trapped particles were ST68 microbubbles (MBs) prepared as described by Basude *et al.*[16] 1.48 g sorbitan monostearate (Span 60), 1.50 g NaCl, and 1.0 ml polyoxyethylene sorbitan monooleate (Tween 80) were well mixed and suspended in 50 ml phosphate buffer saline (PBS). The solution was sterilised at 120 °C for 15 min, and then cool down to room temperature under constant stirring. The final solution was stood for about 35 min to separate into three distinct layers. MBs were then collected from the middle layer and washed three times by PBS. Finally, ST68 MBs were suspended in PBS, and protected by perfluoropropane gas, then sealed and stored at 4 °C. The diameter of MBs is ranging from 500 nm to 5 $\mu$m. In the experiments, MBs are diluted in distilled water ($n$ = 1.33 at room temperature). All of the MBs trapped and manipulated in our experiment were spherical particles.

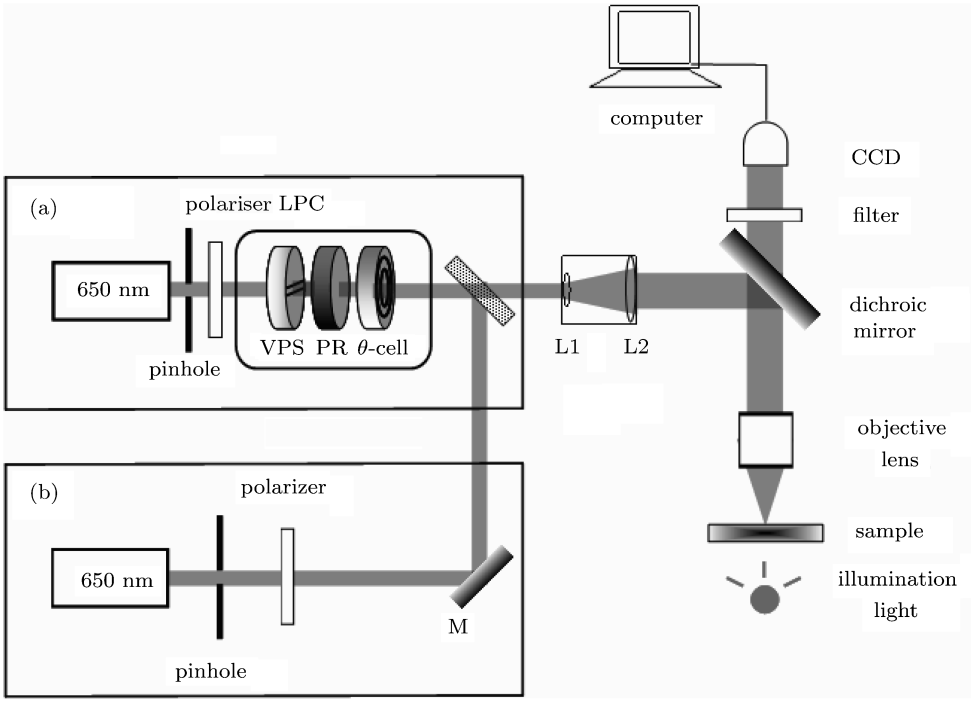



**Fig. 1.** Scheme of the dual optical tweezers system consists of a DMOT and a SMOT. (a) The azimuthally polarised trapping beam, (b) the Gauss trapping beam. LPC: liquid-crystal polarisation converter; VPS: variable phase shifter; PR: polarisation rotator.

## 3. Results and discussion

The intensity distributions, the focal spots and the polarisation pattern of the azimuthally polarised beam and the Gauss beam are shown in Figs. 2(a)–2(c) and Figs. 2(d)–2(f), respectively. As can be seen from the figure, the maximal intensity of the Gauss beam is located at the centre, whereas that of the azimuthally polarised beam is located in a circular ring around the centre. The azimuthally polarised beam is a kind of hollow beams. The electric field in the focal region can be written as[11]

$$\boldsymbol{E}(r,\phi,z) = E_\phi \boldsymbol{e}_\phi, \tag{1}$$

where $\boldsymbol{e}_\phi$ is the unit vector along the azimuthal direction. The amplitude of the azimuthal component can be expressed as

$$\boldsymbol{E}(r,\phi,z) = 2A\int_0^\gamma \sqrt{\cos\theta}\sin\theta \mathrm{J}_1(kr\sin\theta) \times \mathrm{e}^{\mathrm{i}\,kz\cos\theta}\mathrm{d}\theta, \tag{2}$$

where $A$ is the relative amplitude, $\gamma$ is the maximum convergence angle given by the objective lens, $l(\theta)$ is the pupil apodisation function, $k$ is the wave number in the surrounding medium, and $\mathrm{J}_1(x)$ is first-order cylindrical Bessel function of the first kind. The electric field in the focal region of the azimuthally polarised beam only contains transverse component, the longitudinal component is absent, which is notable difference as compared to Gauss beam.

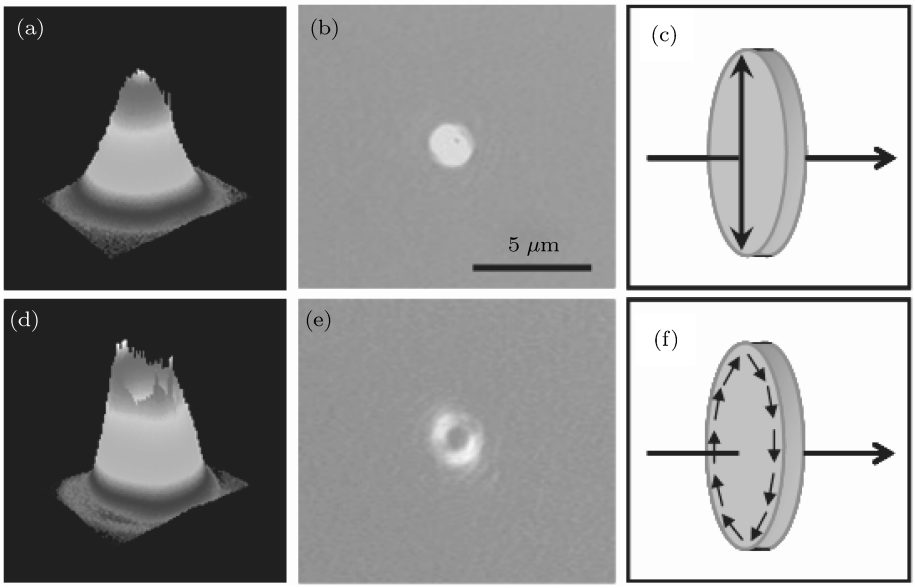



**Fig. 2.** Intensity distributions and polarisation patterns of the Gauss beam (a)–(c) and the azimuthally polarised beam (d)–(f). (a) and (d) 3D intensity distribution; (b) and (e) the focal spots; (c) and (f) the polarisation patterns.

The 3D optical trapping of MBs was achieved with both 40× and 100× objective lenses. The trapping distance from the slide-glass to the cover-glass was 48 $\mu$m. In order to study the axial trapping ability of DMOT and SMOT, comparison between the axial trapping force and the axial trapping effect was performed in DMOT and SMOT. The comparisons of the axial trapping effect were shown in Fig. 3. The same MBs was trapped by DMOT and SMOT, respectively, as shown in Figs. 3(a) and 3(c). For DMOT, when the platform was moved downward, the MBs was still stably located in the hollow core (Fig. 3(b)). For SMOT, in contrast, when the platform was moved downward with the same distance, the MBs was axially released from optical trapping due to the strong scattering force (Fig. 3(d)). This proves that it is very easy for DMOT to trap a MBs axially. The long-distance axial trapping of MBs by DMOT is more stable than that of SMOT.

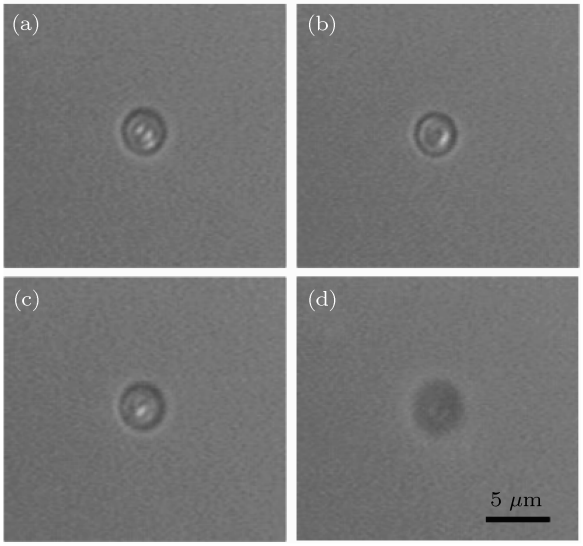



**Fig. 3.** Comparison of axial trapping effect in DMOT and SMOT. A 40× objective lens was used for trapping.

We measured the axial trapping force of a particle with a diameter of 3.5 $\mu$m in DMOT and SMOT systems. The method used to calibrate the axial trapping force was based on the viscous drag exerted by fluid flow according to Stokes' law.[17]

$$F = 6\pi\eta R v, \tag{3}$$

where $\eta$ is the viscosity of the medium, $R$ is the radius of the MBs, and $v$ is the escape velocity at which the MBs is released from the optical trap. To measure $v$, we trapped the MBs near the slide-glass where reduced convective motions allowed the best trapping conditions. The speed of trapped MBs in the axial direction is controlled by adjusting the movement speed of the object stage. The speed of the trapped MBs is increased gradually until the particle fall out of the trap. And the velocity recorded at this time is the escape velocity $v$ of MBs. The quick change between DMOT and SMOT allows direct comparison the axial trapping force of the same trapped MBs. This whole process is repeated for 5 particles with same diameter. Figure 4 shows the average values of axial trapping forces obtained from DMOT and SMOT. According to the experimental results, when the laser power is 45.6 mW, the axial trapping force is 5.88 pN in DMOT and 5.43 pN in SMOT with a 40× objective lens. As can be seen from Fig. 4, using either 40× or 100× objective lens, the azimuthally polarised beam can realise the better axial trapping ability than the Gauss beam. Due to the singularity polarised pattern, the azimuthally polarised beam could form a doughnut intensity distribution when it is tightly focused. It is reported that the axial gradient force is produced primarily by high-angle rays, while small-angle rays only contribute to the scattering force.[18] Thus, the use of doughnut beam, lacking the small-angle rays, should result in improving axial trapping efficiency. Therefore, when the azimuthally polarised beam is used as the trapping beam, the scattering force of DMOT is much weaker than that of SMOT under the same laser power. For the same particle, the escape velocity of DMOT is larger than that of SMOT. That is to say, the axial trapping force of the trapped MBs formed by DMOT is larger than that by SMOT in the same laser power. Therefore, the axial trapping effect is also better. Moreover, the axial trapping force is 5.43 pN with 40× objective lens (NA=0.65) and 5.72 pN with 100× objective lens (NA=1.25) in SMOT when the incident laser power is 45.6 mW. As can be seen from Fig. 4, both in DMOT and in SMOT, the axial trapping force with the 100× objective lens is higher than that with 40× one. Thus, the use of higher NA objective lens can also improve the axial trapping force. However, as previously mentioned, the 5.88 pN axial trapping force could be achieved with a 40× objective lens by DMOT under the same conditions. Obviously, the application of DMOT could increase the axial trapping ability significantly.

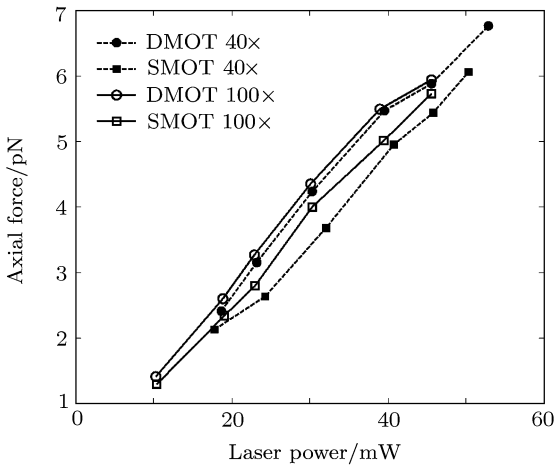



**Fig. 4.** Comparison of axial trapping force depending on the laser power in DMOT and SMOT under 40× and 100× objective lenses.

The stable axial trapping of MBs was achieved by the excellent axial trapping ability of DMOT. A MBs with a diameter of 3.5 $\mu$m (named MBs-A) can be stably trapped with DMOT by moving the objective stage downwards. Figure 5(a) shows that MBs-A is trapped in the core of a hollow beam core. When the objective stage is moved downwards, the MBs-A remains stably trapped within the doughnut-shaped

optical trap, even though the other particle (MBs-B) moves downwards, as shown in Figs. 5(a)–(d).

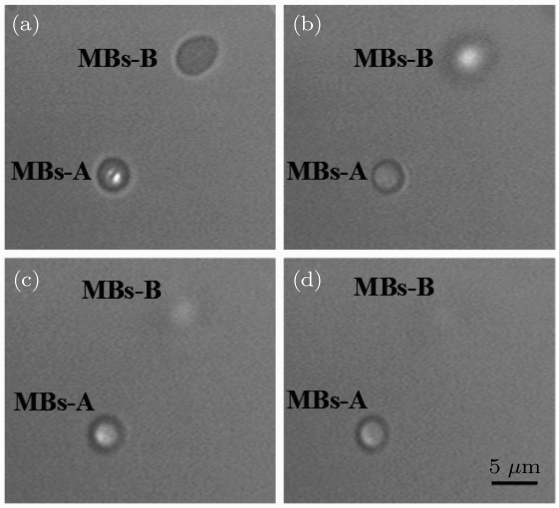



**Fig. 5.** Stable axial trapping of MBs-A by DMOT. A 40× objective lens was used for trapping.

Figure 6 shows the axial trapping force against the laser power $P$ measured for MBs with diameter of 1 $\mu$m, 2.5 $\mu$m and 3.5 $\mu$m, respectively. The measured forces varied between 0.84 pN and 6.76 pN when the laser power was increased from 8.9 mW to 52.9 mW. As shown in Fig. 6, the axial force is proportional to the incident laser power. The higher laser power, the higher axial force is. Moreover, the axial force also depends on the diameter of MBs. According to the electromagnetic theory model ($R \ll \lambda$), theoretical calculations predict that the axial trapping force depends $R^3$. For the geometric optical model ($R \gg \lambda$), the axial trapping force should be related to $R$. And for the situation between the above two models, $F \propto R^a$, where $a = 2.3 \pm 0.1$.[17,18] This means that the axial trapping force would increase with increasing diameter of the MBs.

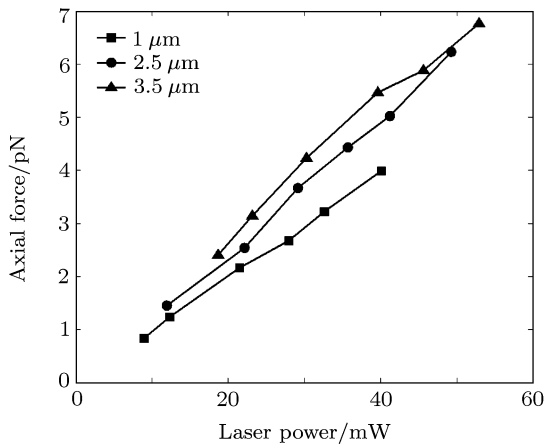



**Fig. 6.** Axial trapping force for different MBs diameter in DMOT.

Therefore, as depicted in Fig. 6, for the particle with diameter of 3.5 $\mu$m, the axial trapping efficiency with DMOT is higher than that for the particles with diameter of 2.5 $\mu$m and 1 $\mu$m.

Moreover, it is worth noticing that the given axial trapping effect can be achieved using DMOT with lower laser power than using SMOT. It is well known that the higher laser power would bring the risk of thermal damage to the trapped particles. So when the given axial trapping effect is achieved, the risk of thermal damage caused by DMOT is much lower than that caused by SMOT. Therefore, DMOT is more suitable for the applications on biology.

The measurement of the axial trapping force and the acquisition of CCD images of trapping effect confirmed that the application of the azimuthally polarised beam could improve the axial trapping ability of optical tweezers. This improvement is helpful for the long-distance manipulation of particles in the axial direction. The construction of DMOT with azimuthally polarised trapping beam can expand the applied field of optical tweezers.

## 4. Conclusions

We have built and tested a dual optical tweezers system based on a semiconductor laser at 650 nm emitting a maximum power of about 100 mW. The dual optical tweezers system is composed of a DMOT with the azimuthally polarised trapping beam and a SMOT with the Gauss beam as trapping beam. The system was operated for trapping MBs with diameter ranging from 500 nm to 5 $\mu$m by using 40× and 100× objective lenses. The axial trapping of MBs was achieved by DMOT and showed more stable than that of SMOT. Axial trapping forces of two type optical tweezers were measured using the viscous drag technology. The results showed that the axial trapping force depended on the diameter of MBs, the laser power, and the NA of the objective lens. The measurement of the axial trapping force and the acquisition of CCD images of trapping effect confirmed that the application of the azimuthally polarised beam could improve the axial trapping ability in optical tweezers. We developed a simple and effective method to improve the axial trapping effect using azimuthally polarised beam as trapping beam, which was helpful for long-distance manipulating of particles in axial direction and will expand the applied field of optical tweezers technology.

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