Optical trap with spatially varying polarization: application in controlled orientation of birefringent microscopic particle(s)

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ABSTRACT We report the use of the interference of two orthogonally polarized beams for generation of an optical trap with spatially varying polarization. The spatial variation of polarization in the optical trap has been used for demonstration of simultaneous rotation or orientation of multiple microscopic birefringent particles. Other potential applications of an optical trap with spatially varying polarization are also discussed.

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1 Introduction

Optical tweezers [1] are being increasingly used for trapping, transport [2], orientation and rotation [3–6] of microscopic objects. The most convenient method for realization of an optically driven motor is to use an elliptically polarized trap beam to transfer spin angular momentum to a birefringent particle [7, 8]. This method has the advantage that a simple control on the ellipticity of polarization of the trap beam can be used to control the speed of rotation of the birefringent particle. For several applications, it would be desirable to simultaneously control multiple rotors with different speed of rotation. One approach recently reported for this objective made use of a spatial light modulator (SLM) and two-dimensional lenslet array to create multiple trapping beams with different polarization state [9]. While this method can provide an independent control of the polarization state of each trap, the separation between the tweezers is limited by the pitch of the lenslet array. Further, a significant loss of power occurs both at the SLM and the lenslet array. In this paper, we report an alternate approach to effect simultaneous rotation/orientation of birefringent particles. The approach exploits a spatial variation of polarization using a polarization grating (PG) [10] in an optical trap created by interference of two orthogonally polarized trap laser beams.

2 Experimental details

For demonstration of the use of PG for alignment and rotation of birefringent particles, interference of two orthogonally polarized beams split from the Nd:YAG laser was used to generate a uniform intensity trap having spatial variation of the polarization vector of the resultant electric field. The experimental set up (Fig. 1) consists of a zero order Hermite–Gaussian (TEM_{00}) mode output of continuous-wave (cw) Nd:YAG laser (1064 nm; Solid State Laser Division, CAT, Indore, India) expanded using a beam expander (BE), and linearly polarized using a thin film polarizer (POL) having an extinction ratio better than 100:1. The beam was split into two paths using a 50/50 beam splitter (BS1) and a half-wave plate (HWP) was inserted in one path to make the polarization of one of the two beams orthogonal to the other. The two beams were then combined using another beam splitter (BS2) and coupled to a 100 × Plan Neofluor phase objective (MO) (N.A. = 1.3) through the base port of the microscope (Axiovert 135 TV, Carl Zeiss). A cylindrical lens (CL) having the same focal length as that of the spherical tube lens (TL) of microscope was used in the path of the two orthogonally polarised beams to collimate the combined beam. The optical delay between the two orthogonally polarized beams was kept within the coherence length of the source. The two laser beams were focused to an elliptical spot in the specimen plane of MO and were made to overlap at a small angle, by carefully tilting M1 and BS2. The visible light from a halogen lamp (HAL), reflected by the dichroic beam splitter (DBS) was sent to a commercial video CCD camera with monitor to visualize the trapping of the microscopic object(s). To prevent the back-scattered laser light reaching the CCD detector, an IR cut-off filter (CF) was used. The motion of trapped object was recorded on a videocassette using a VCR. These images were digitized using a frame grabber and computer. The laser beam power at the back aperture of the objective was monitored with

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a power meter (Scientech, USA). The transmission factor of the objective was estimated to be 0.57 using the dual objective method, which is able to account for the total internal reflection losses at the objective-oil-glass-water interfaces. The power of the Nd:YAG laser beam was varied so as to obtain total power up to 250 mW at the focal plane. A small crystal of calcite was crushed to produce micrometer-sized birefringent particles. These were later suspended in deionized water. A centroid detection software developed on LabView platform was used to monitor position of particle(s) inside the line trap. For CCD pixel size of 6.7 µm, the position of 1-µm sized particles could be determined with a precision of about 25 nm.

3 Results and discussion

When two beams having orthogonal polarization interfere in a medium, the resultant intensity is constant in the region implying that there is no intensity grating. However the polarization of the resultant electric field vector would vary spatially [10] from linearly polarized to left circularly polarized (LCP), to linearly polarized, right circular polarized (RCP) and then back to linear polarized as shown in Fig. 2a. It may be noted that the grating spacing is given by \( \Lambda = \lambda/2n\sin\theta \), where \( \lambda \) is the wavelength of the laser beam, \( n \) is the refractive index and \( \theta \) is the half angle of the interfering beams. By changing the angle between the interfering beams the fringe spacing could be varied. In order to position particles with spacing of \( \Lambda \), an intensity grating was formed (first panel, Fig. 2b) by having the same polarization for the two beams. Tracking a particle inside the line trap having intensity grating provides an easy way to get a priori information on grating spacing. By polarizing the two interfering beams orthogonally by insertion of a half-wave plate (HWP) in the path of one of the beams a polarization grating with uniform intensity across the trap was formed (second panel, Fig. 2b).

Since the linear polarization component orients the birefringent particle and circular polarization component tries to rotate it, variation of the relative magnitude of these components along the trap could be exploited for orienting or rotating the object at varying speeds. Orientation/rotation of a 1.5 µm birefringent particle inside the line trap having polarization grating is shown in Fig. 3. The object was translated along the line trap by moving the translation stage. The viscous drag of the surrounding medium caused the object to move along the major axis of the trap in frames a–d in Fig. 3a. For each spatial location, the orientation of the particle is shown at three time frames separated by 40 ms. By measuring the distance between the two spatial locations where the particle oriented in the same direction, the