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Optical forces on patterned particles

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ABSTRACT

The non-conservative nature of optical forces has been explored previously, with the initial focus on spherical particles, and latterly on particles with less than spherical symmetry. Non-conservative optical forces occur in many different guises, and include lateral forces arising from shape asymmetry, polarisation dependant optical torques and spin-dependant lateral forces. Photo-induced curing of liquid crystalline polymers is a technique that may be used to generate refractive-index patterning of surfaces. Here, we use computational methods to examine the influence of such surface structuring on optically-generated forces and torques, with a view to optimising such materials for applications as light-driven sensors and actuators.

Keywords: Optical forces, sensors and actuators, optical binding, nanopatterning, light robotics

1. INTRODUCTION

It is well known that light can exert forces on microscopic particles which can be exploited for a range of biological and physical applications.[1,2] By shaping the particles used in the tweezers it is possible to tailor the size and direction of the optical forces, increasing the range of potential applications.[3–6] Such shape-induced optical forces have been exploited, for example, in the "optical AFM".[7–9] Furthermore, it has been predicted that optically bound arrays of particles will give rise to non-conservative motion, should the arrangement of the particles be asymmetric.[10,11] Experimental verification of this effect has been published recently.[12] In a separate line of research, metamaterial surfaces have also been shown to experience optical forces, and there are indications that the periodic nature of the substrate may enhance the optical forces that are generated.[13,14]

Patterned two-dimensional surfaces, both metallic and dielectric, may be fabricated using a range of different lithographic techniques, and could form the basis of optically controlled sensors and actuators. In the current paper, we perform a preliminary simulation study on the optical forces that can be generated by various two-dimensional patterned dielectric surfaces. We start by assuming a particular *motif*, which has sufficient asymmetry to exhibit a lateral optical force i.e. the force is in a direction perpendicular to the propagation direction of the illumination beam. The motif is then replicated and the influence of multiple scattering on the total force generated is assessed.

2. METHODS

The system is modelled as a thin film of high refractive index material on a lower refractive index substrate. Plane wave illumination was assumed, normally incident on the substrate. A wavelength of $\lambda = 1\mu$m was used with the thickness of the motif taken as 0.1λ. The motif chosen consists of two dielectric discs of maximum diameter 1λ, and separated by 1λ (see Fig. 1). The left hand disc is fixed at 1λ while the right hand disc is allowed to vary in size as the optical force is computed. For symmetry reasons, the only non-zero component of optical force will be directed horizontally in the figure. In all calculations both horizontal and vertical linear polarisations will be considered.

All optical force calculations were performed using the discrete dipole approximation (DDA) approach, either using in-house code, or the freely available ADDA program.[15–17] For simplicity the assumption was made that

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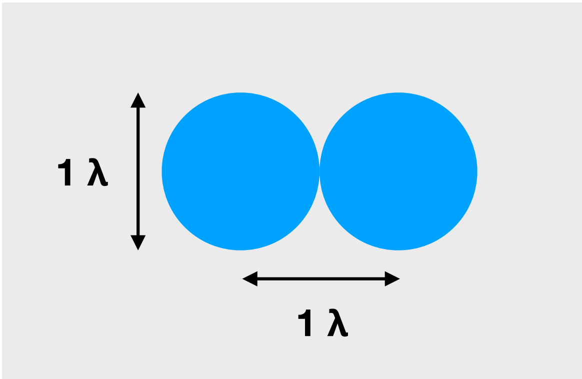


Figure 1. Schematic representation of the motif used in the optical force calculations. The left hand disc is fixed at 1λ while the right hand disc is allowed to vary in size and the horizontal component of force (positive to the right in the figure) is found.

the system was immersed in an index-matching oil, so that reflections from the substrate could be ignored in the DDA calculations. Forces are quoted in scaled units, such that:

$$F = \frac{F_{rad}}{I_0} = \frac{m_0 C_{pr}}{c}, \tag{1}$$

where m_0 is the refractive index of the surrounding medium, C_{pr} is the radiation force cross-section and I_0 is the incident intensity.

3. RESULTS AND DISCUSSION

In the results which follow, the dimensions of a single motif are adjust first to maximise the optical force that is generated. This is followed by an examination of the effect of different stacking arrangements of multiple motifs on the overall force.

3.1 Single motif

The structure motif shown in Fig. 1 is modified by changing the diameter of the right hand disc, while keeping the separation between the discs constant. The results are shown in Fig. 2. As expected, the optical force is zero when the two discs are of equal size. On reducing the right hand disc diameter, variations are observed in the optical force generated with both incident polarisations. The horizontally polarised field induces a maximum force when the right hand disc has a diameter of 0.6λ. The position of the maximum is due to an interplay between the increasing asymmetry, as the diameter decreases, and decreasing scattering. Interestingly, the vertical polarisation gives rise to a maximum at the same diameter, but goes through two large negative values, at around 0.3 and 0.9λ. Immediately, this suggests the possibility that both the amplitude and the sign of the optical force could be controlled by varying the polarisation state of the incident beam.

3.2 Vertically arranged pairs of motifs

As shown in Fig. 3(a), two motifs are arranged vertically on the substrate, with centres separated by the distance x. As x is increased from 1μm (motifs in contact), the horizontal force arising from horizontally polarised light passes through a maximum and appears to oscillate (see Fig. 3(b)). On the other hand, the vertically polarised light increases from close to zero, and passes through a maximum at about 1.6μm. Interestingly, the juxtaposition of the two motifs leads to an order of magnitude increase in the optical forces predicted.

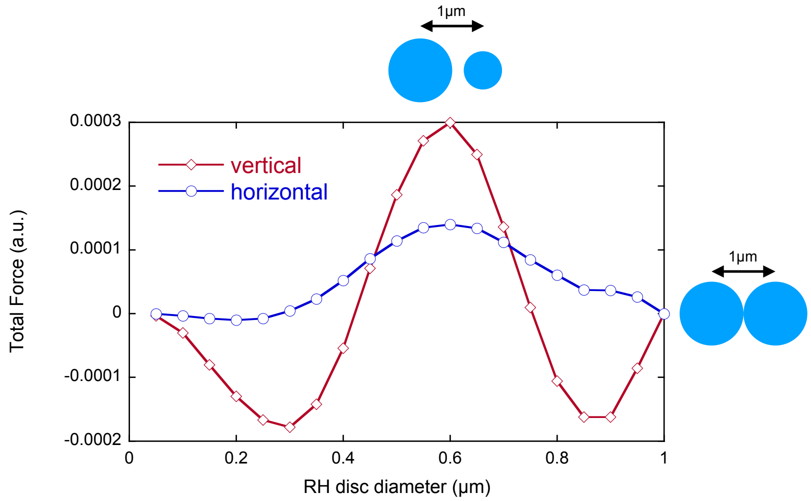
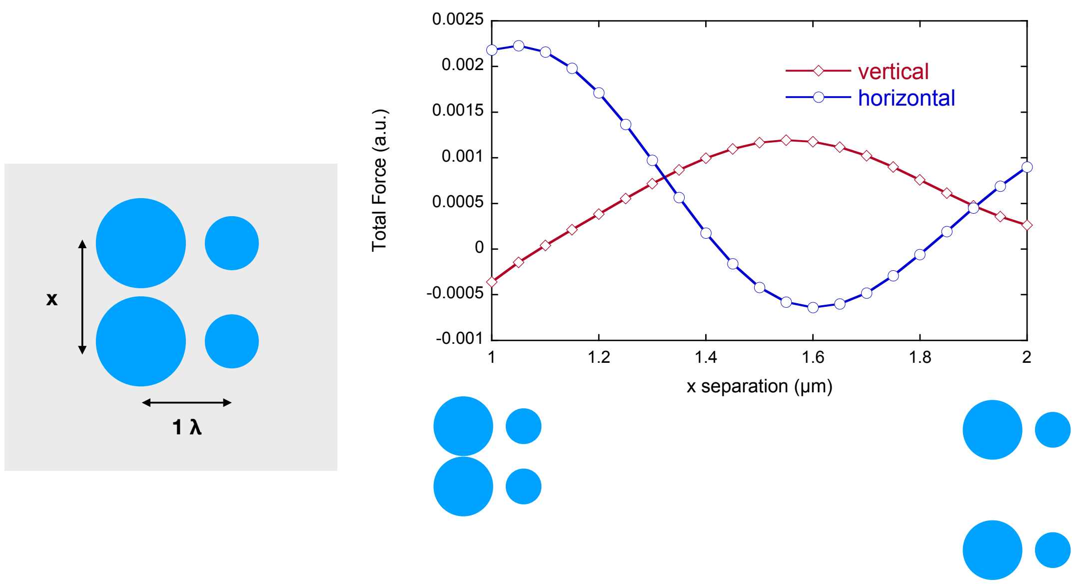


Figure 2. Graph showing the horizontal optical force as a function of the diameter of the right-hand disc in a pair of discs, for vertical (red line) and horizontal (blue line) polarisations of the incident beam.

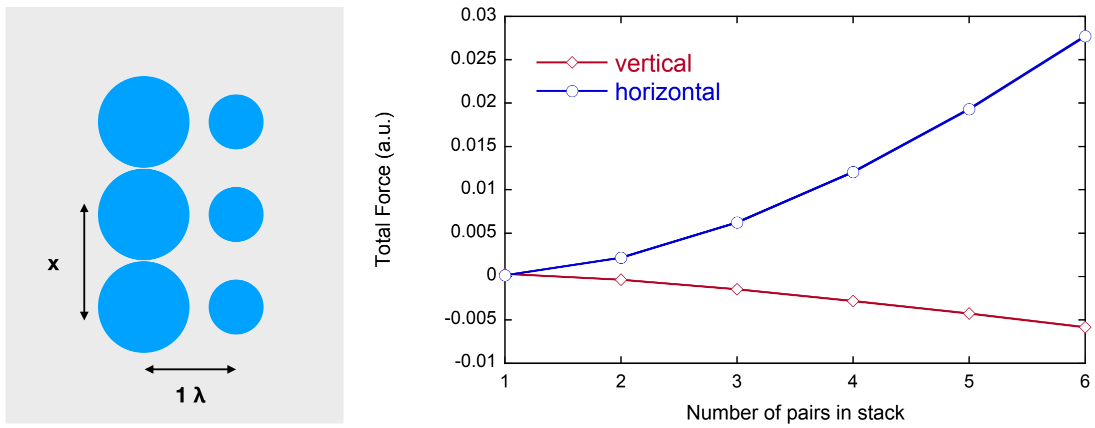


(a) (b)

Figure 3. (a) Schematic arrangement of vertical pairs of disc motifs. (b) Graph showing the horizontal optical force as a function of the vertical separation, x, of a pair of disc motifs, for vertical (red line) and horizontal (blue line) polarisations of the incident beam.

3.3 Vertical stack of motifs

Increasing the number of motifs in a vertical stack arrangement further enhances the optical force generated. In Fig. 4 the motifs are placed in contact ($x = 1\mu$m) which, in the case of two motifs (Fig. 3) gave close to the maximum horizontal force. As more motifs are added in the same configuration, the optical force increases non-linearly so that, for six motifs, i.e. three times as many scattering centres, the total optical force has increased by more than an order of magnitude. In fact, when compared with the forces obtained from a single motif (Fig. 2) the overall force has increased by two orders of magnitude.

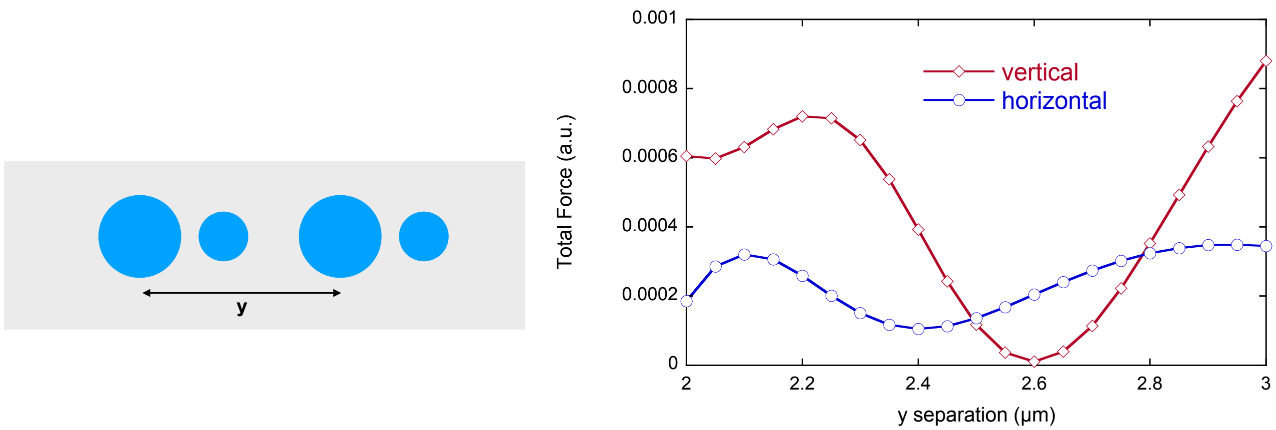


(a) (b)

Figure 4. (a) Schematic arrangement of a vertical stack of disc motifs. (b) Graph showing the horizontal optical force as a function of the number of motifs in the stack, for a fixed value of vertical separation, $x = 1\mu$m, for vertical (red line) and horizontal (blue line) polarisations of the incident beam.

3.4 Horizontal pair of motifs

If a pair of motifs are separated horizontally, there is also an enhanced optical force, although the effect is not so great as when the pair are arranged vertically. In Fig. 5 the separation, y, between a pair of motifs is varied between 2 and 3μm. When $y = 2\mu$m, the left hand small disc is equidistant between two larger discs and, similarly, the right hand large disc is equidistant between two small discs. It is likely that this degree of local symmetry contributes to some cancelling of forces. There is a marked difference in behaviour between the two polarisations: the force induced by the horizontal polarisation has two maxima, at $y = 2.1\mu$m and 2.9μm, but does not go to zero in this range, while that due to the vertical polarisation is three times larger at the closest separation, goes to zero for $y = 2.6\mu$m but then appears to increase greatly for larger y. This needs to be investigated further.



(a) (b)

Figure 5. (a) Schematic arrangement of a horizontal pair of disc motifs. (b) Graph showing the horizontal optical force as a function of the horizontal separation of the motifs, y, for vertical (red line) and horizontal (blue line) polarisations of the incident beam.

3.5 Block of motifs

Figure 6 shows a 2×4 arrangement of motifs, measuring approximately $4\times4\mu$m. The parameters have been chosen based on the above discussion to optimise the optical force generated. In this case, the horizontal separation is taken as $y = 2.1\mu$m while the vertical separation is $x = 1\mu$m. The horizontal component of force calculated for this arrangement is $F_y = 0.015$ a.u. This represents a 25% increase in optical force as compared with a single vertical stack of four motifs (as shown in Fig. 4).

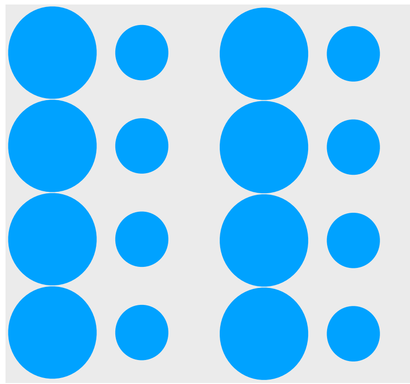


Figure 6. Schematic representation of a block of motifs measuring approximately $4 \times 4\mu$m. The vertical separation between motif centres is $x = 1\mu$m while the horizontal separation is $y = 2.1\mu$m.

4. CONCLUSIONS

The results discussed above demonstrate the effect on induced optical forces if a simple motif is replicated periodically in two dimensions. Significant differences in optical force were observed between horizontal and vertical polarisations of the incident beam, in some cases including a reversal of the force. In consequence it appears that the size of optical force induced could be controlled by controlling the linear polarisation state of the beam. As might be expected, the magnitude of the optical force depends on the polarisation, the size of the scatterer relative to optical wavelength, the refractive index and the symmetry or shape of the motif. Most notably, with a minimal adjustment of stacking geometry, it has been possible to increase the horizontal optical force by two orders of magnitude. It seems likely that other choices of motif could give rise to similar enhancements, and a study of this is ongoing.

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