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OPTICAL TRAPPING WITH FEMTOSECOND PULSES: EXCITEMENTS, CHALLENGES AND OPPORTUNITIES

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Abstract

Theories and experiments on optical trapping under femtosecond pulsed excitation demonstrated that the force/potential acting on, and hence the ensuing dynamics of, the particles is quite different from that under continuous-wave excitation, owing to optical and thermal nonlinearities. In this paper, we revisit the progress in this field, elucidating the key concepts and potential applications through exploiting optical nonlinearity.

Introduction

Recent theoretical and experimental works from our group [1-9] showed that the nature of optical trapping force/potential under continuous-wave (CW) excitation and femtosecond pulsed excitation (at the same time-averaged power) is distinctly different. Under pulsed excitation, optical and thermal nonlinearities can dramatically modulate the force/potential acting on the particles, and hence the course of particles' trapping dynamics. In this paper, we elucidate the concept of 'escape potential', arising from nonlinear optical force under femtosecond pulsed excitation, which was first theoretically envisaged for particles of varying sizes [1-7]; subsequently, it was validated through meticulous experiments [7-9] which also revealed the critical role played by thermal nonlinearity manifested by observation of an 'adjustment dynamics'. We further elaborate how we can harness optical nonlinearity to have far-reaching applications in facile and controlled optical manipulation.

Results and discussion

Refraction of light through a translucent non-absorbing particle gives rise to a three-dimensional *gradient force* that would try to restore the particle to the geometric focus whenever it moves away from the focus; on the other hand, reflection of light imparts a one-dimensional *scattering force* that tries to push the particle forward, i.e. along the beam propagation direction. Therefore, the net force acting on the particle along the direction transverse to the beam propagation is always restoring in nature; however, the net force along the beam propagation direction results from a balance between scattering force and axial component of gradient force and the overall stability of the trap relies on this delicate balance.

Now, under femtosecond pulsed excitation, optical nonlinearity sets in which renders part of the refractive index dependent on intensity of light. Due to dependence of gradient and scattering force on light intensity to different extent, the trapping force/potential on the particle is dramatically modulated which can be controlled by excitation parameters (for example, power/intensity, pulse-width, etc) as well as by material properties (nonlinear refractive index, particle-size, etc).

Let us now compare the theoretical results simulating the nature of axial force/potential under CW and femtosecond pulsed excitation. In Figure 1, the force and potential are plotted for 100 mW CW excitation. The resulting potential along axial direction is asymmetric (and has a minimum slightly ahead of geometric focus) due to addition of (conservative) gradient force and (non-conservative) scattering force.

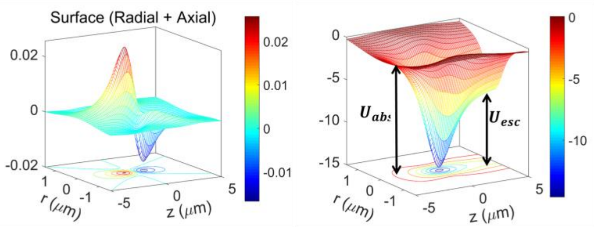

Figure 1 *Force (left panel) and potential (right panel) on an 80 nm diameter polystyrene bead under CW excitation at 100 mW time-averaged power.*

The asymmetry is more for femtosecond pulsed excitation at the same time-averaged power, which is evident from Figure 2.

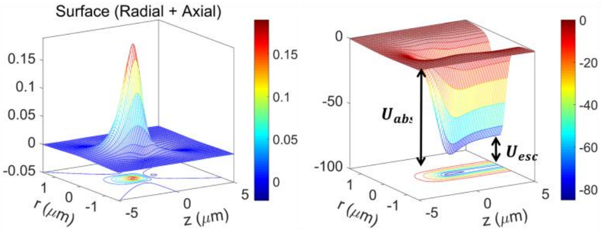

Figure 2 *Force (left panel) and potential (right panel) on an 80 nm diameter polystyrene bead under femtosecond pulsed excitation at 100 mW time-averaged power.*

While escaping the trap, the particle is most likely to overcome the lower-side of the potential barrier and be ejected in the forward direction. Therefore, it is imperative to investigate the behaviour of this potential barrier to escape the trap, termed as escape potential (U_{esc}) [1], with laser power.

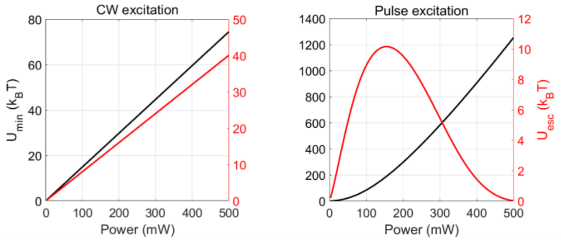

Figure 3 *Variation of absolute potential (black curves) and escape potential (red curves) with increasing time-averaged power for CW excitation (left panel) and femtosecond pulsed excitation.*

As shown in Figure 3, while the absolute well depth, termed as absolute potential (U_{abs}), monotonically increases under both excitations, under femtosecond pulsed excitation the escape potential maximizes at a particular average power before falling off to zero. Therefore, for such excitation, there exists an optimal power corresponding to most stable trap which refutes the widely accepted rule-of-thumb that a higher power would lead to more stable trapping.

Although the results shown here are based on dipole approximation calculation (in the Rayleigh scattering limit) [1, 5], the same were shown to hold using different theories [3, 6] and for different particle-size limits [2, 4, 6].

One crucial observation in the experiment on micron-sized particles [7] was that, following a steep rise (due to initial dragging of the particle toward trap centre), the backscatter signal drops from its peak value by certain amount and remain constant as long as the particle resides inside the trap; by changing the viscosity of the medium, this drop in signal was attributed to the movement of the trapped particle to a new equilibrium position contributed by the delayed action of thermal nonlinearity.

As theoretically envisaged, optical nonlinearity can be harnessed for facile optical manipulation involving reversal of force on hollow-core dielectric nanoparticles [10-11], multi-particle trapping (due to trap-splitting) [12] and force reversal (due to Fano resonance) for metallic nanoparticles [13], enhanced force on layered (core/shell type) dielectric and hybrid nanoparticles [14], and so on.

On a final note, despite these stimulating results, a rigorous theoretical description for thermal nonlinearities incorporating hydrodynamic effects (for example, laser induced convection) in the medium and thermal nonlinearity due to presence of the particle is yet to be formulated. From, experimental point-of-view, synchronization among variation detection modalities, to have simultaneous spatial and temporal resolution, is yet to be explored. These new horizons are presently being pursued in the author's lab.

Conclusion

To conclude, the salient features of optical trapping under femtosecond pulsed excitation are elucidated and its potential applications are summarized.

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