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Optical cooling and trapping: introduction

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The year 2015 is an auspicious year for optical science, as it is being celebrated as the International Year of Light and Light-Based Technologies. This focus issue of the journals *Optics Express* and *Journal of the Optical Society of America B* has been organized by the OSA Technical Group on Optical Cooling and Trapping to mark this occasion, and to highlight the most recent and exciting developments in the topics covered by the group. Together this joint focus issue features 33 papers, including both experimental and theoretical works, which span this wide range of activities.

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1. INTRODUCTION

In 2015, the International Year of Light and Light-Based Technologies (IYL2015) will highlight the importance of light and optical technologies for the social, economic, and scientific development of the world. The year 2015 is significant for many reasons, including marking 20 years since the first realization of an atomic Bose–Einstein condensate, 45 years since the invention of optical trapping, the centennial of Einstein's theory of general relativity, 150 years since Maxwell's theory of electromagnetic waves, 200 years since Fresnel's proposition of the wave nature of light, and 1000 years since Ibn al-Haytham's treatise on Optics. In recent years, progress in optics and optical physics has been recognized and highly rewarded, as is amply demonstrated by counting the number and frequency of Nobel prizes in the field: in 1997, for the development of methods to cool and trap atoms with laser light; in 2001, for the achievement of Bose–Einstein condensation in dilute gases of alkali atoms; in 2005, for contributions to the quantum theory of optical coherence and for the development of laser-based precision spectroscopy; in 2008, for the discovery and development of the green fluorescent protein; in 2009, for the CCD sensor and transmission of light via optical fibers; in 2012, for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems; and in 2014, for the invention of efficient blue light-emitting diodes (physics) and for the development of super-resolved fluorescence microscopy (chemistry) to name but a few of the more recent achievements. All Nobel laureates whose citation relates to light and light-based technologies can be found at the OSA's website [1].

2. OPTICAL COOLING AND TRAPPING: SUMMARY OF CONTRIBUTIONS

In recognition of IYL2015, the OSA Technical Group on Optical Cooling and Trapping has arranged this joint focus issue of the OSA journals *Optics Express* and the *Journal of the Optical Society of America B*. Although the remit of the Technical Group covers only a subset of optical physics, the activities of researchers within the group are themselves very broad, being concerned with all aspects of the physics of laser cooling, electromagnetic trapping, and other radiative manipulation of matter. The technique is applied widely to objects ranging from neutral atoms and ions to nanostructures, dielectric particles, and biological specimens. It encompasses both fundamental studies, e.g., Bose–Einstein condensates, cold atom collisions and optomechanics, and applications to new kinds of physics measurements and processes such as high resolution spectroscopy, atomic clocks, biomolecular interactions, and atomic- and nano-scale fabrication. Research activities span the range from technical instrumentation to highly refined theoretical advances.

This diversity of interest in the field is well represented by the papers in this focus issue which have been grouped into themes to reflect some of the most recent activities and trends.

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A. Laser Cooling, Including Bose–Einstein Condensation

Papers on this theme concern laser cooling and manipulation of atomic species both as vapor and in the condensed phase. This includes both atomic Bose–Einstein condensates and laser cooling of optomechanical systems.

In 1832, Hamilton discovered and predicted mathematical conical refraction. In this focus issue, Turpin *et al.* [2] use this effect for simulating the trapping of Bose–Einstein condensates for the first time. The conical refraction from the incident Gaussian beam results in a set of two concentric bright rings enclosing a dark ring of minimal intensity, known as the Poggendorff dark ring. This dark optical ring potential is of great interest for ultra-cold atoms; it leads to reduced atom heating and decoherence rates. This work concludes with some possible applications and future investigations.

In [3], the authors explore a new material for optical cooling. It is shown that ytterbium-doped glass ceramics shows the best measured cooling figures-of-merit of these samples, based on optical calorimetry because of the reduced non radiative decays.

Ruhrig *et al.* [4] report on efficient demagnetization laser cooling of an atomic cloud by suppression of light-assisted collisions by exploiting selective optical pumping into a dark state. This is a novel scheme that promises an efficient route to all-optical condensation.

Can laser cooling be realized without spontaneous emission? Apparently it can, as highlighted in the paper by Corder *et al.* [5]. The authors review the historical motivation for the need for spontaneous emission to dissipate entropy. Using a technique of bichromatic forces, and only stimulated processes, this is achieved as demonstrated by simulations and experimental measurements.

Bowman *et al.* [6] demonstrate the use of a spatial light modulator at several widely separated wavelengths to make tailored optical trapping potentials for use in ultracold atom experiments. This method makes it possible to write different spatial patterns for each of the different wavelengths which then overlap in a certain restricted region of the Fourier plane. This technique has the potential to be used to generate optical potentials for neutral atoms with sub-diffraction limited spatial features.

Two papers in this focus issue are concerned with brightening, that is, increasing the flux of cold atoms in an atomic beam. In [7], Glover and Bastin investigate the use of spectrally broadened laser light for cooling and collimating an atomic beam. They show that such a “white light” molasses can be advantageous over other atomic collimation techniques because of a larger velocity capture range and relatively simple experimental implementation. By contrast, in [8], Fang *et al.* present a compact magneto-optic trap from which a beam of atoms is extracted by a pushing laser beam, countered by a retarding one. The flux of atoms derived from this source is found to be higher because of the use of a hollow retarding beam which suppresses a loss-mechanism inherent in earlier experiments.

A theoretical investigation of rotational cavity optomechanics is carried out by Bhattacharya [9]. He examines the optomechanical interaction between a rotating nanoparticle and an optical cavity mode carrying orbital angular momentum, and shows that the nanoparticle rotation frequency is imprinted on the probe optical mode via the Doppler shift. This rotational optomechanical coupling may be sensed using homodyne detection.

Ivanov *et al.* [10] present a new mechanism of laser cooling of crystals doped with rare-earth ions. The mechanism involves cooling cycles including two-photon Raman scattering through the dipole-allowed 5d ion level, electron-phonon transitions between the Starksplit sublevels, and fluorescence from the excited ion level. It is theoretically shown that the involvement of dipole-allowed transitions yields an increase in the cooling efficiency compared to the efficiency of the traditional scheme based on the 4f transitions.

Rosanov and Vysotina [11] theoretically study the dynamics of an atomic soliton under a time-dependent trapping potential. Under certain situations, the dynamics can be described by a Newtonian equation. The results help to investigate various structures of matter waves in traps.

Hung *et al.* [12] present a systematic study on the atomic life time in an optical dipole trap derived from a multimode fiber laser. This paper reveals the loss mechanism of Rb atoms in the trap because of Raman transitions and optical pumping effects induced by multi-frequency modes of lasers. They also provide methods to avoid such loss, specifically for Rb atoms.

Eerkens *et al.* [13] discuss a room temperature measurement of sideband cooling a mechanical object with a 10^{-10} kg mass, which is a bit more massive than those that have been sideband cooled. The frequency of the resonator is a few times less than a MHz, compared to MHz mechanical objects that have been cooled previously. By using high-quality Bragg mirrors, they construct a cavity and show its operation in the sideband resolved regime. Ground-state cooling and quantum superposition of such a macroscopic optomechanical system will appear within reach.

B. Force Calculation and Measurement in Optical Traps

Papers in this section concern the calculation of forces on particles in a variety of optical trapping schemes, including traditional optical tweezers, waveguide traps, and optical binding. They explore the effect of particle shape and material (including plasmonic behavior), and of novel beam geometries. They also include experimental techniques for the measurement of such forces.

The current standard calibration technique in optical tweezers involves the use of back focal plane interferometry to measure the position of a trapped particle. Another approach is to use a direct force measurement method, based on the complete knowledge of the scattered field. In [14], the authors have demonstrated that the total force in the axial direction, measured by the direct method, can be determined to a precision of under 1%, for sizes and refractive indexes of a typical biological sample. This is achieved by compensating the nondetected transmitted scattered field by considering the intensity in the back-scattered image.

In [15], the authors have demonstrated the importance of consideration of multiple scattering in determining the optical force on a particle in the evanescent field near an optical waveguide. Through the use of the T-matrix formalism, it is shown that multiple scattering between the particle and the waveguide has a significant effect for particles with large refractive index contrast to their surroundings, even leading to a repulsive force from the waveguide for large particles.

In [16], Bradshaw and Andrews proposed that a trapping beam with defined circular polarization allows for enantiomer separation. The calculation method involves using quantum electrodynamics to determine the optical trap potential energy, evidencing the magnetic dipole contribution as the one that contributes the most toward this chiral differentiation force.

Does nanoparticle shape matter for stable equilibrium in an optical tweezers? Apparently it does; according to [17], gold nanoparticles assume icosahedron, triangular prism, and other irregular shapes, as imaged by electron microscopy. The theoretical simulations, based on the discrete-dipole-approximation, agree with experimental results from other groups, thus leading to the argument that optical trapping forces are enhanced when certain plasmon resonances are excited, playing a significant role for the trapping of metallic nonspherical nanoparticles.

In [18], Callegari *et al.* present a complete computational toolbox that can provide robust results for the calculation of optical forces and torques for dielectric particles with a variety of shapes in optical tweezers. The calculations are made under the geometrical optics approximation of optical trapping applicable to relatively large particles, and the authors have made the toolbox available to download.

The work by Sukhov *et al.* [19] discusses calculations of optical binding of an asymmetric material system where non-reciprocal interactions between particles can take place. In such systems, non-conservative forces can arise on the center of mass of optically bound dissimilar particles with consequent occurrence of unexpected transverse forces.

The behavior of one and two spheroidal particles optically trapped has been experimentally and numerically investigated [20]. The trap consisted of a counter-propagating beam carrying opposite spin angular momentum, but no net linear momentum. The complex behavior of the spheroidal particle is described in terms of the main axis, rotation frequencies, and aspect ratio—all in good agreement with calculations.

Accurate calculations of optical forces by pulsed beam optical tweezers are discussed by du Preez-Wilkinson *et al.* [21] in the generalized Lorenz–Mie or T-matrix framework and when nonlinear effects are negligible. They present results for femtosecond pulses of various widths, and compare them with forces due to a continuous wave (CW) beam. For particle size close to the trapping wavelength, they find that the difference in forces between a pulsed tweezers and a CW one can be quite significant in a range of 3%–8%, depending on the pulse width. This method can serve to determine where nonlinear effects are likely to occur or as a basis for testing potential future methods that include the nonlinear effects in the force calculation.

Optical trapping forces on complex metal nanostructures are simulated by Pan *et al.* [22]. They exploit a hybrid method that combines finite element and boundary integral calculations. Numerical results indicate that the proposed method can accurately and efficiently predict the plasmonic effects as well as optical trapping forces. This offers a viable route to model optical forces on complex metallic nanostructures with fast convergence and reduced computational demand.

The properties of frozen waves, i.e., suitable superposition of equal-frequency Bessel beams, are theoretically described by Ambrosio and Zamboni-Rached [23] in the context of the generalized Lorenz–Mie theory. They report on calculations of radiation pressure cross sections and beam shape coefficients, showing numerically that, under the paraxial regime, frozen waves could be designed to efficiently trap particles along multiple radial planes and at specific axial locations leading to reinforce frozen waves as potential laser beams in optical trapping and manipulation. In a second paper [24], Ambrosio and Ferreira extend the study of optical trapping with frozen waves to a range of particles in the Rayleigh regime, including both high- and low-index dielectric, magnetodielectric and hypothetical negative index particles, thereby reinforcing the potential these beams hold for micromanipulation.

C. Trapping Schemes and Applications

Papers in this section are concerned with novel schemes for the realization of optical traps, including beam shaping in optical tweezers and optical fiber traps. They include the use of optical traps for manipulation and quantitative measurements on particles such as plasmonic nanostructures and biological cells, and this section also features a complete guide to building an optical tweezers with advanced manipulation and force-measurement capabilities.

Controlled optofluidic trapping and manipulation is presented by Gong *et al.* in [25] using a tapered graded-index fiber (GIF). Stable trapping is achieved by balancing fluid flow and optical forces on microscopic particles. Control over the stable trapping position is achieved either by varying the balance between these forces or by changing the degree of focusing from the tapered GIF. An adjustable length microcavity at the input of the GIF allows the location of the output focus, and hence trapping position, to be tuned over a wide range, thus permitting long-range manipulations to be realized.

Pu and Jones [26] demonstrate optical trapping using a beam shaped by an optical element that has a phase profile derived from a fractal set—a "devil's vortex lens." The optical trap is used for both dielectric microparticles and metallic nanoparticles, and the optical force is characterized.

In [27], Mondal *et al.* demonstrate an asymmetrical scattering from nonspherical particles in an optical trap that suffers from spherical aberration. This results in a net tangential force revolving up to a few Hertz in an optical ring trap and motion of the passive particles which mimics that of microswimmers (so-called "active matter"). Experimental results are compared to finite-difference time-domain simulations.

A technique is proposed to trap microparticles above and between a gap of two planar waveguides [28]. The particles are confined near the waveguide by evanescent fields; at the end of the waveguides the diverging field traps and lifts microparticles above the planar waveguide surface. This strategy keeps trapped particles away from the surface, which is easily integrated in lab-on-a-chip devices.

The authors in [29] present an instructive step-by-step guide (with a complete list of parts needed) to construct a single-beam optical tweezers, which can also be upgraded to achieve holographic optical trapping or implement a speckle optical trap. Particle tracking via digital video microscopy and light scattering (back focal plane interferometry) are described and calibration techniques using acquired data compared. Furthermore, the authors have made their software for data analysis and trap hologram calculation available to download.

Messina *et al.* [30] discuss quantitative optical trapping measurements of silver nanoplatelets obtained with a simple room temperature wet chemistry approach. They show how optical trapping forces scale with different diameters find a two-dimensional scaling behavior and a good agreement with calculations based on dipole approximation and T-matrix. Applications of these novel plasmonic particles to surface-enhanced Raman spectroscopy are also discussed.

A key application of optical tweezers and optical stretchers has been the probe of viscoelastic properties of biological cells. An accurate full three-dimensional modeling of the cell viscoelastic response is discussed by Yu and Sheng [31]. They show mechanical and finite element analyses of the cell elongations in both creep and dynamic regimes.

Porfirev and Skidanov [32] report on a technique for generating dark-hollow optical beams with a controllable cross-sectional intensity distribution by superposing Bessel beams. By exploiting this technique, they are able to demonstrate photophoresis-based optical trapping and manipulation of absorbing airborne nanoclusters.

Finally, Pesce *et al.* in [33] map the electrophoretic and dielectrophoretic forces from a tip, producing strong electric field gradient. This was realized by monitoring a negatively charged polystyrene microsphere acting as a probe in an optical tweezers under an oscillating electric field, yielding forces below 1 pN.

3. CONCLUSION

We hope that the present focus issue will encourage further experimental and theoretical work in this exciting and diverse field. We would like to thank all the authors who have contributed to this issue, as well as all the anonymous reviewers who dedicated their time and expertise in the assessment of all submitted manuscripts. We offer special thanks to the Editors-in-Chief of *Optics Express* and the *Journal of the Optical Society of America B*, and to the OSA staff, who supported and guided this issue. Finally, the guest editors warmly invite scientists to join the OSA Technical Group on Optical Cooling and Trapping.

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