Nan LI, Xun-min ZHU, Wen-qiang LI, Zhen-hai FU, Meng-zhu HU, Hui-zhu HU, 2019. Review of optical tweezers in vacuum. *Frontiers of Information Technology & Electronic Engineering*, 20(5):655-673.
https://doi.org/10.1631/FITEE.1900095

Review of optical tweezers in vacuum

Key words: Optical tweezers, Optical trapping in vacuum, Optical cooling

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Motivation

- Optical tweezers in vacuum, eliminating the primary source of dissipation present for most inertial sensors, attracted much attention in both fundamental and applied physics.
- Remarkable progress in trapping micro-scale and nanoscale spheres at high vacuum pressures has been achieved in recent years, but no specific review with an intensive survey was published yet.
- A review of the history and the basic concepts of optical tweezers in vacuum would provide an overall understanding of the field.

Main idea

1. Basic theory and experimental scheme of optical tweezers in vacuum

- Principle of optical trapping --- build a physical picture including radiation force and optical cooling theory
- Fundamental techniques in building optical tweezers in vacuum

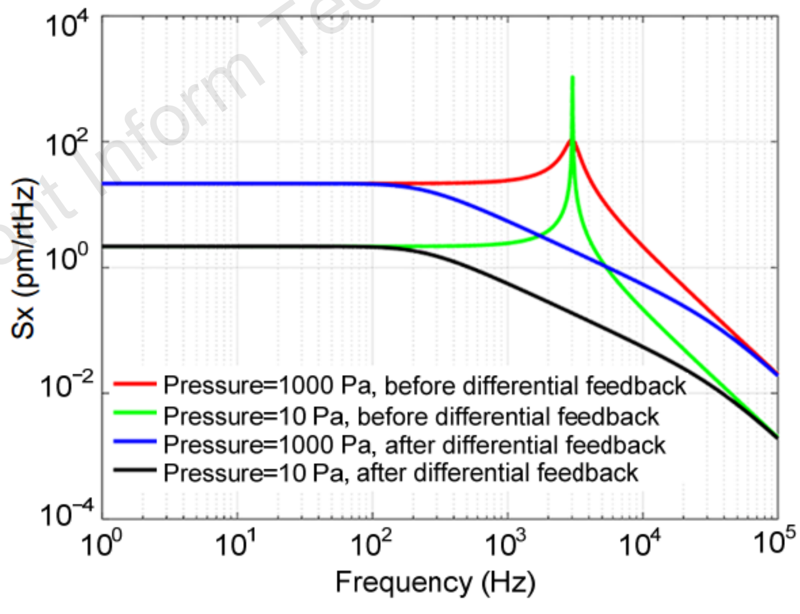
2. State-of-the-art progress in vacuum optical tweezers field

- Force sensor, accelerometer, micro-gyroscope, and frontier research like macroscopic quantum state

Illustrative demonstration

1. Simulation of the PSD of particle displacement with differential cooling and air pressure reducing conditions

- The PSD of particle displacement in the low frequency range decreases only when air pressure drops
- Particles under green line conditions are more likely to escape unless there exists efficient cooling



Illustrative demonstration

2. A survey of reported diverse optical configurations for trapping particles in vacuum is listed

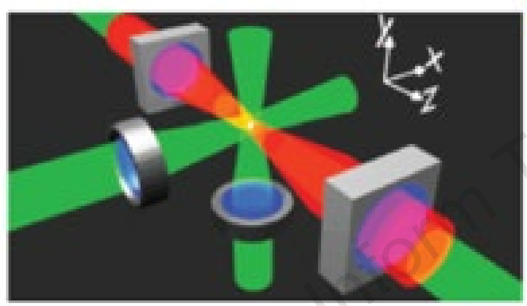
Optical configuration	Particle material & diameter	Numerical aperture	Laser & power	Cooling method	Equivalent temperature	Vacuum pressure (mbar*)	Reference
Counter-propagating in-coherent beams	Silica, 3 μm	0.680	~50 mW per beam	Differential feedback	150, 1.5, and 68 mK for the *x*, *y*, and *z* modes, respectively	5.2E-5	Li et al. (2011)
Counter-propagating in-coherent beams	Silica, 3 μm	~0.075	~120 mW per beam	Differential feedback	10, 55, and 12 K for the *x*, *y*, and *z* modes, respectively	6.7E-6	Ranjit et al. (2015)
Counter-propagating co-herent beams	Silica, 300 nm	~0.075	~120 mW per beam	Differential feedback	400 mK for the one mode	5.0E-6	Ranjit et al. (2016)
Upward single beam	Silica, 14 μm	0.03	~200 mW	Differential feedback	~7/5 mK for the *x* mode	1.0E-6	Monteiro et al. (2017)
Single beam	Silica, 140 nm	Not mentioned	Not mentioned	Parametric feedback	150, 400, and 50 mK for the *x*, *y*, and *z* modes, respectively	1.0E-6	Gieseler et al. (2012)
Single beam	Silica, 100 nm	0.9	Not mentioned	Parametric feedback	145 μK for the *y* mode	6.9E-9	Jain et al. (2016a)
Single beam	Silica, 75 nm	0.8	1064 nm ~100 mW	Parametric feedback	Not mentioned	5.0E-7	Gieseler et al. (2012)
Single beam	Silica, 177 nm	0.77	1565 nm 540 mW	No cooling	Not mentioned	~1.0E-6	Torki (2016)
Single beam	Silica, 170 nm nanodumbbell	0.85	1550 nm 500 mW	No cooling	Not mentioned	~1.0E-4	Ahn et al. (2018)
Single beam with parabolic mirror	Silica, 64 nm	0.995	385 mW	Parametric feedback	13, 6, and 3 mK for the *x*, *y*, and *z* modes, respectively	6.0E-6	Vovrosh et al. (2017)

* 1 mbar=100 Pa

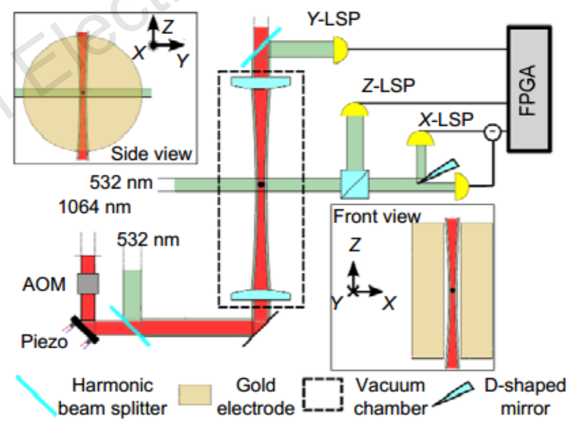
Illustrative demonstration

3. Reported applications including force measurement (a), acceleration measurement (b), gyroscope effect study (c), and macroscopic quantum state (d) are demonstrated.

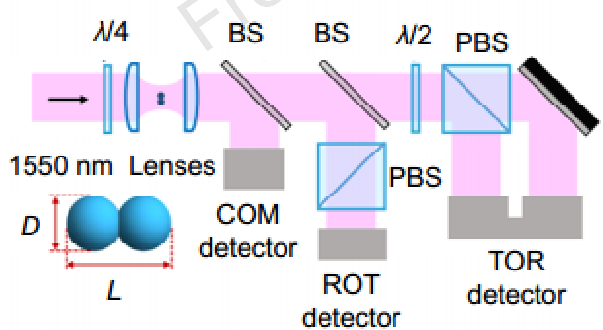
(a)



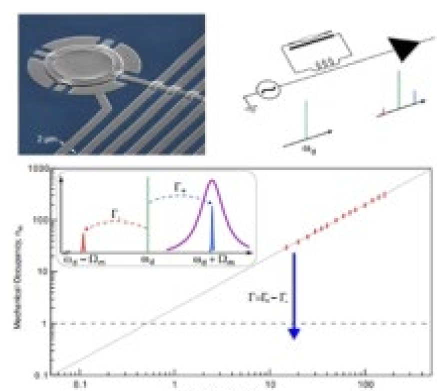
(b)



(c)



(d)



Summary

- Fundamental concepts of optical trapping, cooling, and detection were discussed.
- An intensive survey of progress in vacuum optical tweezers was given.
- The development trend in this field was proposed and analyzed.