Tailoring Optical Forces Through Electromagnetic Field Manipulation Using Auxiliary Structures

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2018 December 27

Outline

1 Scientific question

2 Scientific Background and State of the Art
- Optical Forces
- Optical Nanostructures
- Guided wave optics

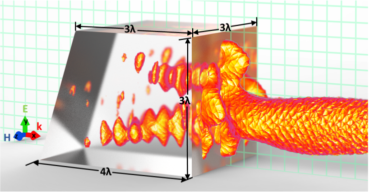
3 Results

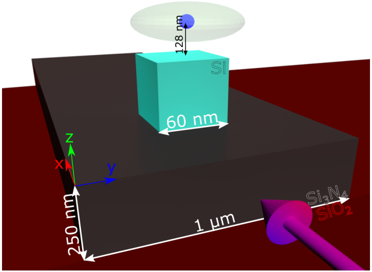
4 Methodology and Workflow

5 Publications and Presentations

Research aims

My work aims to explore and design nanostructures for generating electromagnetic fields with the goal of using these fields for two specific optical manipulation applications.





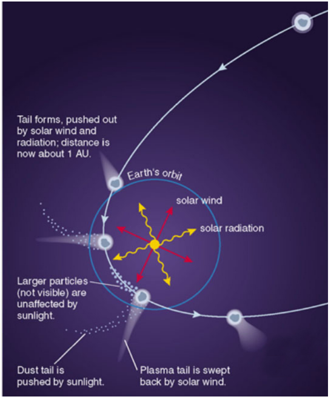
Research aims and significance

1. **Particle sorting and differentiation using forces along curved trajectories**: Using only a dielectric cuboid, I will study a method of generating forces that can move particles along curved paths.

Research aims and significance

2 **All-dielectric structures for atomic trapping**: Through the use of a patterned overlayer on top of an all-dielectric waveguide system, I propose that it is possible to create multiple intensity gradients to trap multiple atoms in a loss-less manner.

History: Radiation Pressure



- First hypothesized in 1619 by Kepler to explain why comet tails point away from the Sun.
- The idea that light, with its associated momentum, can exert forces on surfaces was first published by Maxwell in 1862.
- Proven experimentally by Levedev in 1900 and Nichols and Hull in 1901 by shining light on a thin mirror, it was shown that the forces from radiation pressure are very small.

http://lasp.colorado.edu/education/outerplanets/kbos_comets.php

Principles of Optical Forces

In general, the time-averaged optical force acting on a particle is obtained through the integration of the Maxwell Stress Tensor **T** over a closed surface ∂V surrounding the probe particle[2]:

$$\langle \mathbf{F} \rangle = \int_{\partial V} \langle \mathbf{T}(\mathbf{r}, t) \rangle \cdot \mathbf{n}(\mathbf{r}) \, \mathrm{d}A. \tag{1}$$

For numerical simulations, this method of obtaining optical forces is computationally intensive.

[2] L. Novotny and B. Hecht, *Principles of Nano-Optics*. United Kingdom: Cambridge University Press, 2006.

Principles of Optical Forces

We will consider the case when the radius of the particle is significantly smaller than the incident wavelength of the field. Using the Taylor expansion, we now get[3,4]

$$\langle \mathbf{F} \rangle = \frac{1}{2}\mathrm{Re}[(\nabla \mathbf{E}_i^*) \cdot \mathbf{p}] + \frac{1}{2}\mathrm{Re}[(\nabla \mathbf{B}_i^*) \cdot \mathbf{m}] - \frac{k^4}{12\pi\epsilon_0 c}\mathrm{Re}[\mathbf{p} \times m^*] + \ldots \quad (2)$$

This work deals with only the first term in Eq. (2), which corresponds to the force if the probe were assumed to be only an electric dipole.

[3] L. Novotny and B. Hecht, *Principles of Nano-Optics*. United Kingdom: Cambridge University Press, 2006.

[4] J. Chen, J. Ng, Z. Lin, and C. T. Chan, Optical pulling force, Nat Photon, vol. 5, no. 9, pp. 531534, Sep. 2011.

Principles of Optical Forces

The first term of Eq. (2) can be written in the following form:

$$\langle \mathbf{F} \rangle = \frac{\alpha'}{4} \nabla E_0^2 + \frac{\alpha''}{2} E_0^2 \nabla \phi \tag{3}$$

where α is the probe's complex polarizability. For a spherical particle, this is given by[5]

$$\alpha = 4\pi r^3 \epsilon_0 \frac{\epsilon_p - \epsilon_a}{\epsilon_p + 2\epsilon_a} \tag{4}$$

[5] B. T. Draine, The Discrete-Dipole Approximation and its Application to Interstellar Graphite Grains, The Astrophysical Journal, vol. 333, pp. 848872, 1988.

Principles of Optical Forces

Using the equation of the EM field intensity, the first term in Eq. (3) can be written as[6,7]

$$\langle \mathbf{F}_{\mathrm{dip}} \rangle = \frac{1}{2\epsilon_0 c} \alpha' \nabla I(\mathbf{r}). \tag{5}$$

This is a *conservative force*, hence it can be written in terms of a scalar potential, $\mathbf{F} = -\nabla U$. The associated scalar potential function is then given by

$$U_{\mathrm{dip}} = -\frac{1}{2\epsilon_0 c} \alpha' I(\mathbf{r}) \tag{6}$$

[6] I. Bloch, Ultracold quantum gases in optical lattices, Nature Physics, vol. 1, no. 1, pp. 2330, Oct. 2005.

[7] R. Grimm, M. Weidemller, and Y. B. Ovchinnikov, Optical Dipole Traps for Neutral Atoms, Advances In Atomic, Molecular, and Optical Physics, vol. 42, pp. 95170, Jan. 2000.

Principles of Optical Forces

In the case where we want to use these optical forces to trap atoms, the polarizability α is different.

From Eq. (6), the potential for linearly polarized incident fields can be derived as[8]

$$U_{\mathrm{dip}}(\mathbf{r}) = \frac{\pi c^2 \Gamma}{2\omega_0^3} \left(\frac{2}{\Delta_2} + \frac{1}{\Delta_1} \right) I(\mathbf{r}) \quad (7)$$

where Δ is defined as the detuning of the incident field from the atomic resonance frequency,

$$\Delta \equiv \omega - \omega_0. \quad (8)$$

[8] R. Grimm, M. Weidemller, and Y. B. Ovchinnikov, Optical Dipole Traps for Neutral Atoms, Advances In Atomic, Molecular, and Optical Physics, vol. 42, pp. 95170, Jan. 2000.

Principles of Optical Forces

For frequencies below the atomic resonance, $\Delta < 0$, which is referred to as *red-detuned*, the dipole potential is negative, hence the interaction attracts atoms into the light field.

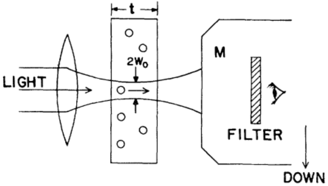
On the other hand, frequencies above the atomic resonance ($\Delta > 0$), called *blue-detuned*, repels atoms out of the field.

In order to neglect the spontaneous emission effects from resonant excitations, the incident laser light is far-detuned from the atomic resonance frequency, hence the resulting dipole potential is as described in Eq. (6), and is purely conservative[9]

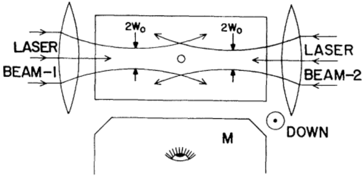
[9] I. Bloch, Ultracold quantum gases in optical lattices, Nature Physics, vol. 1, no. 1, pp. 2330, Oct. 2005.

Optical Force Experiments

Experiments in optical trapping were first shown by Ashkin (Nobel Prize in Physics recipient 2018) using focused laser beams.[10,11]



(a)



(b)

[10]A. Ashkin, Acceleration and Trapping of Particles by Radiation Pressure, Phys. Rev. Lett., vol. 24, no. 4, pp. 156159, Jan. 1970.

[11]A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and S. Chu, Observation of a single-beam gradient force optical trap for dielectric particles, Opt. Lett., OL, vol. 11, no. 5, pp. 288290, May 1986.

Optical Tweezers for Biological applications

- For biological applications, the polarization α is very low due to the low permittivity contrast of the probe and environment; hence a high-power and highly-focused incident field is required for this application.
- The highly-focused incident field required to trap particle raises the problem of heating - in addition to the potential for altering or damaging the biological samples, the heating can also influence the motion of the targets due to thermophoretic effects[12].

[12] J. E. Baker, R. P. Badman, and M. D. Wang, Nanophotonic trapping: precise manipulation and measurement of biomolecular arrays, WIREs Nanomed Nanobiotechnolgy, Apr. 2017.

Lattice Optical Tweezers

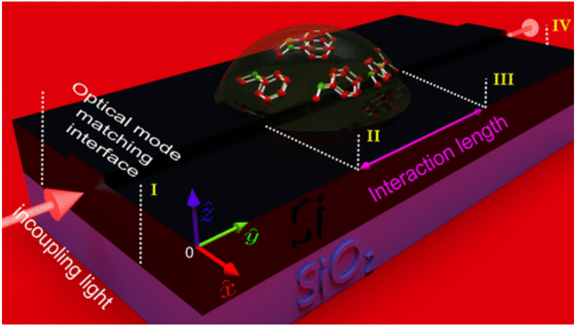
- For trapping and manipulating multiple objects simultaneously, options to do so include: holograms, interference fringes, counter-propagating beams, etc. These methods can be used for applications such as particle sorting or fabrication of metamaterials and photonic devices.
- These methods have been proven to work, but these require very precise alignment and specialized equipment.

Optical Nanostructures

Over the last few decades, a new goal of controlling the optical properties of materials has emerged. A wide range of technological developments could be made possible by engineering materials to respond to a specific range of frequencies.

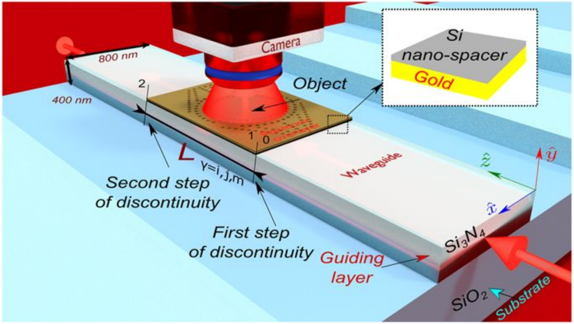
An example is the optical fibers; these simply guide light, but have already revolutionized the telecommunication industry. Many other fields could also benefit from advances in optical materials.

Optical Nanostructures



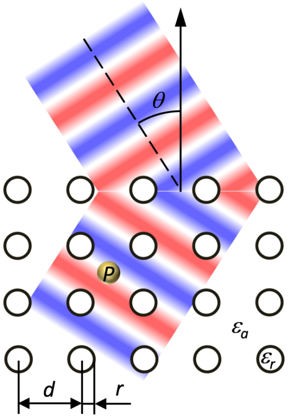
A. Katiyi and A. Karabchevsky, Si Nanostrip Optical Waveguide for On-Chip Broadband Molecular Overtone Spectroscopy in Near-Infrared, ACS Sensors, vol. 3, no. 3, pp. 618623, Mar. 2018.

Optical Nanostructures



Y. Galutin, E. Falek, and A. Karabchevsky, Invisibility Cloaking Scheme by Evanescent Fields Distortion on Composite Plasmonic Waveguides with Si Nano-Spacer, Scientific Reports, vol. 7, no. 1, Dec. 2017.

Applications of Nanostructures

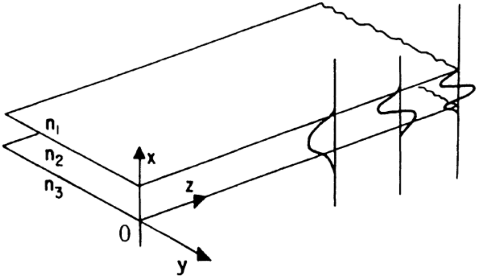


- In my previous work, I showed the movement of a particle immersed in the left-handed field of a photonic crystal.
- I selected a particle such that the scattering forces would dominate in the system. I studied if it would be possible to create a pulling force from this set-up.
- (short) result: no.

A. S. Ang, S. V. Sukhov, A. Dogariu, and A. S. Shalin, Scattering Forces within a Left-Handed Photonic Crystal, Scientific Reports, vol. 7, p. 41014, Jan. 2017.

Optical Waveguides

Electromagnetic waves travel through waveguides in distinct optical modes - a spatial distribution of energy in one or more dimensions that remains constant in time.[16]



[16] R. G. Hunsperger, Integrated optics: theory and technology, 6th ed. New York; London: Springer, 2009.

Optical Waveguides

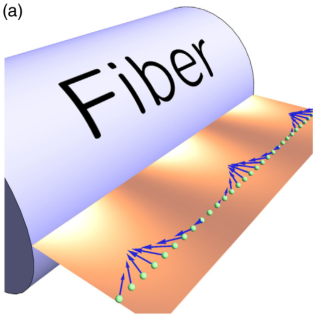
The general solution for the Maxwell Equations for a slab waveguide is given by

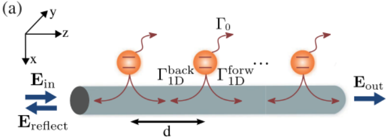
$$\mathcal{E}_y(x) = \begin{cases} = A\exp(-qx) & 0 \leq x \leq \infty \\ = B\cos(hx) + C\sin(hx) & -t_g \leq x \leq 0 \\ = D\exp\left[p\left(x + t_g\right)\right] & -\infty \leq x \leq -t_g \end{cases} \tag{9}$$

where A, B, C, D, are field constants which can be obtained by applying the boundary conditions and q, h, and p are the propagation constants, t_g is the slab thickness.[17]

[17] R. G. Hunsperger, Integrated optics: theory and technology, 6th ed. New York; London: Springer, 2009.

Waveguides in Atomic Trapping



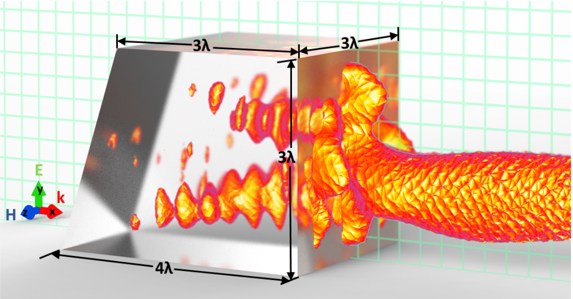


N. V. Corzo et al., Large Bragg Reflection from One-Dimensional Chains of Trapped Atoms Near a Nanoscale Waveguide, Physical Review Letters, vol. 117, no. 13, Sep. 2016.

H. L. Sørensen et al., Coherent Backscattering of Light Off One-Dimensional Atomic Strings, Phys. Rev. Lett., vol. 117, no. 13, p. 133604, Sep. 2016.

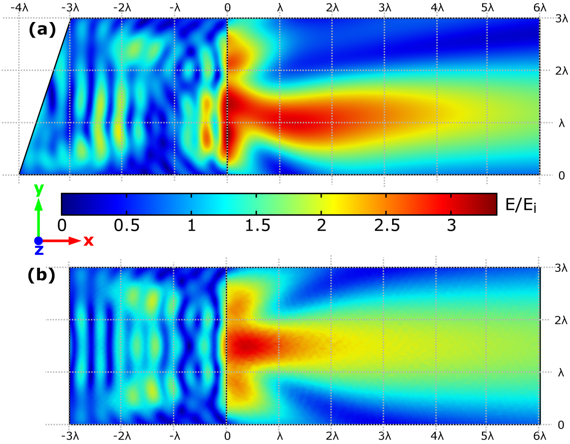
Preliminary results: photonic hook

In this subtask, we consider the following dielectric cuboid geometry:

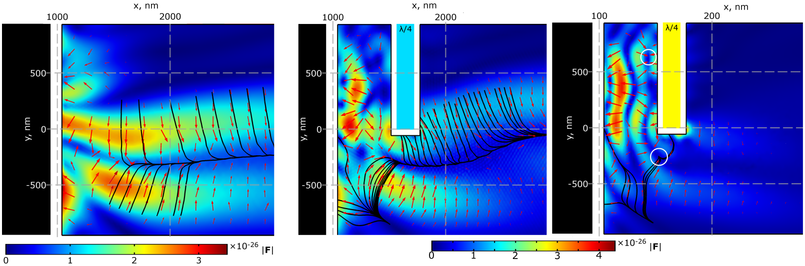


The incident field is a plane wave of 625 nm, and the cuboid has refractive index of 1.46.

Preliminary results: photonic hook



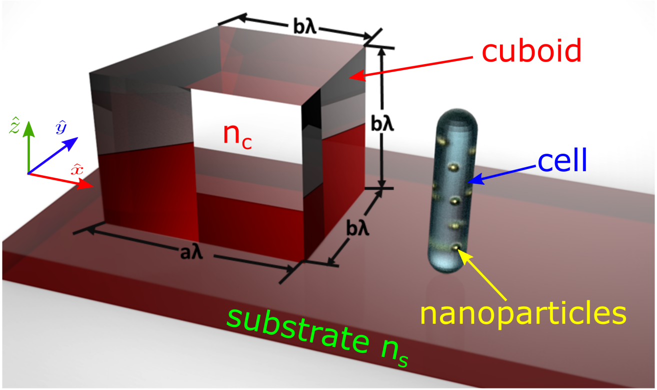
Preliminary results: photonic hook



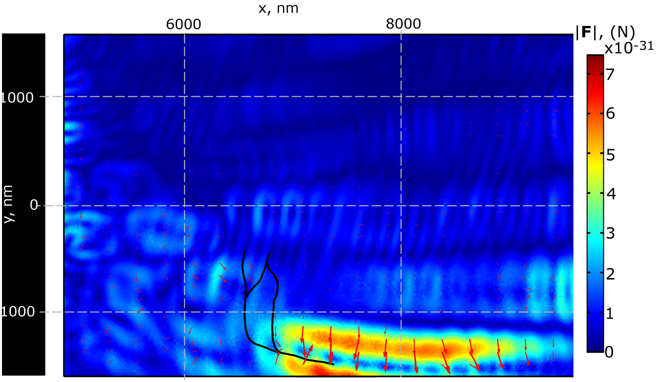
Preliminary results: photonic hook

Photonic hook animation

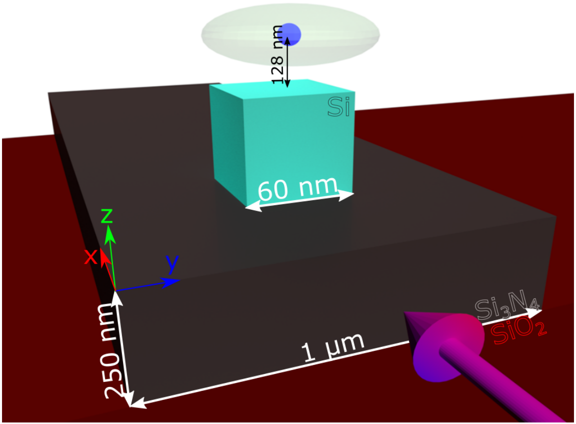
Preliminary results: photonic hook



Preliminary results: photonic hook

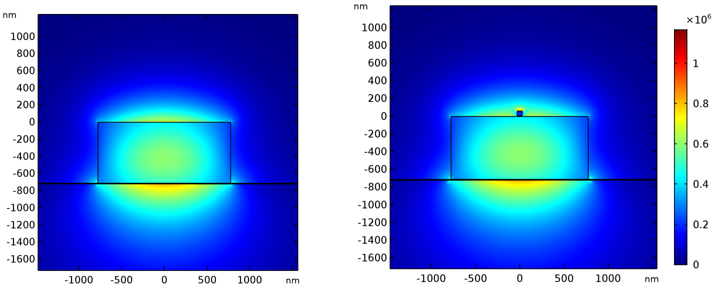


Preliminary results: atom trapping



Preliminary results: atom trapping

For an incident field of 2400 nm, adding a subwavelength Silicon cube changes the field on top of the waveguide.



Preliminary results: atom trapping

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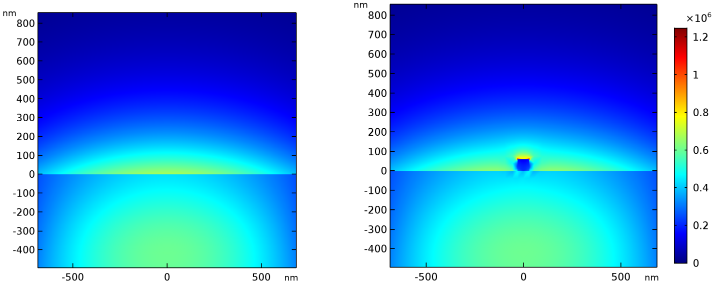
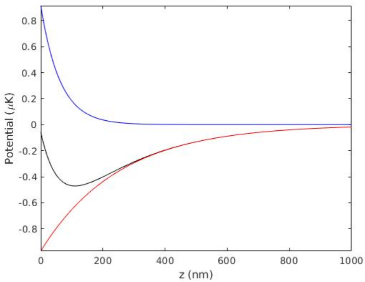
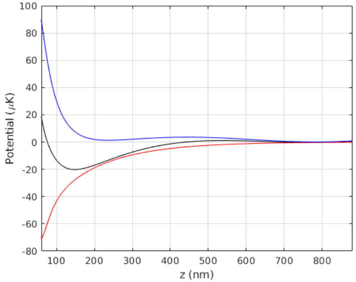
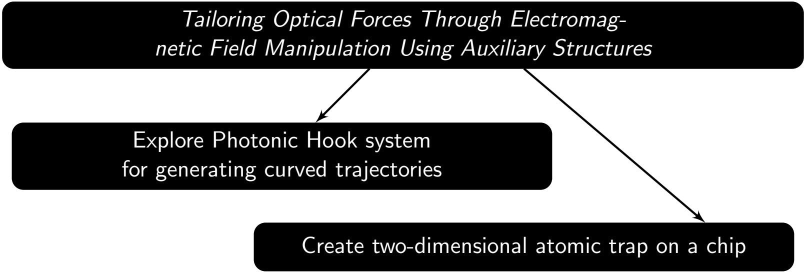


Preliminary results: atom trapping





Methodology



Methodology

Explore Photonic Hook system for generating curved trajectories

↓

Literature review of Photonic Nanojets and the Photonic Hook

↓

Create simulation of photonic hook

↓

Calculate forces using the two methods. Confirm results.

↓

Explore different obstacle scenarios for applications

↓

Consider set-ups for cellular differentiation

Methodology

Create two-dimensional atomic trap on a chip

↓

Literature review of various approaches in atomic/optical trapping

↓

Study of waveguide structures, modes, guided-wave optics

↓

Overlayer simulation for single-atom trapping

↓

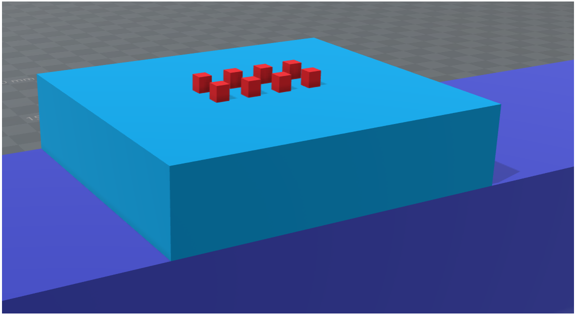
Obtain potential from evanescent field using bichromatic light

↓

Add Casimir-Polder and/or van der Waals potential contributions

Methodology: Future Plans

Once we have obtained realistic values for sting-atom trapping using our proposed waveguide structure, we plan to extend the number of atoms trapped in a waveguide by adding more nano-antennas of varying sizes on top of the waveguiding layer.



Methodology: Future Plans

…

↓ Engineer the metasurface to flatten the evanescent field for trapping a line of atoms

↓ Add the forces from non-optical sources

↓ Show that the potentials form a series of minimum points along a line

↓ Design the metasurface to trap more atoms along the direction of field propagation

↓ Include the additional forces

↓ Confirm that the potentials shows a grid of minimum potential wells

Publications and Presentations

Journal articles

1. **A. S. Ang** et al., All-dielectric waveguide-nano-antenna system for single-atom optical trapping, *in preparation*.
2. **A. S. Ang**, A. Karabchevsky, I. V. Minin, O. V. Minin, S. V. Sukhov, and A. S. Shalin, Photonic Hook based optomechanical nanoparticle manipulator, Scientific Reports, vol. 8, no. 1, p. 2029, Feb. 2018.

Conference papers

1. **A. S. Ang** et al., All-dielectric waveguide-overlayer system for single-atom optical trapping, presented at the Nano.IL 2018 conference, Jerusalem, Israel, 2018. (poster)
2. **A. S. Ang**, I. V. Minin, O. V. Minin, S. V. Sukhov, A. S. Shalin, and A. Karabchevsky, Low-contrast photonic hook manipulator for cellular differentiation, presented at the META 2018, the 9th International Conference on Metamaterials, Photonic Crystals and Plasmonics, France, 2018, p. 2. (Invited talk)
3. **A. S. Ang**, I. V. Minin, O. V. Minin, S. V. Sukhov, A. S. Shalin, and A. Karabchevsky, Photonic Hook as Nanoparticle Manipulator, presented at When Light Meets Matter, Weizmann Institute, Israel, 2018. (poster)