Light-on-a-Chip Group

Electrooptical Engineering

ITMO UNIVERSITY

BGU

Directional scattering of light by silicon nanoparticles and nanostructures due to high-order multipoles contribution

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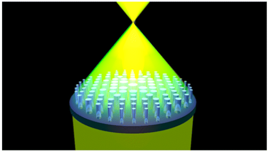
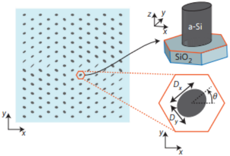
Outline

Motivation

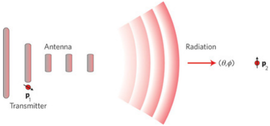
Possible Applications



Khorasaninejad M. et al. **'Polarization-insensitive metalenses at visible wavelengths.'** Nano Letters 16.11(2016): 7229-7234.

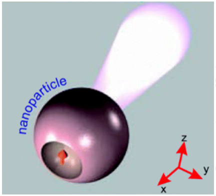


Arbabi A. et al. **'Dielectric metasurfaces for complete control of phase and polarization with subwavelength spatial resolution and high transmission.'** Nature nanotechnology 10 (2015): 937-942

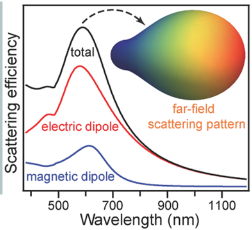


Novotny L., Van Hulst N. **'Antennas for light.'** Nature photonics 5.2 (2011): 83-90

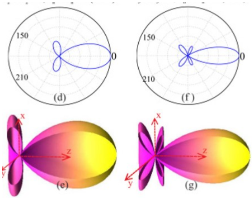
Directional Scattering by high-index nanoparticles



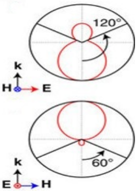
Krasnok A. E. et al. **'Superdirective dielectric nanoantennas.'** Nanoscale 6:13 (2012): 7354-7361



Zhang S. et al. **'Colloidal Moderate - Refractive - Index Cu_2O Nanospheres as Visible - Region Nanoantennas with Electromagnetic Resonance and Directional Light-Scattering Properties.'** Advanced Materials 27.45(2015): 7432-7439.



Liu W. et al. **'Ultra-directional forward scattering by individual core-shell nanoparticles.'** Optics express 22.13(2014): 16178-16187



Paniagua-Domnguez R. et al. **'Generalized Brewster effect in dielectric metasurfaces.'** Nature communications 7 (2016): 10362

Methods

Multipole decomposition method

Regular electric dipole moment of the scatterer

$$\mathbf{p} = \int \mathbf{P}(\mathbf{r}')d\mathbf{r}'$$

Toroidal dipole moment, having **the same radiation pattern**

$$\mathbf{T} = \frac{i\omega}{10}\int \{2\mathbf{r}'^2\mathbf{P}(\mathbf{r}') - (\mathbf{r}'\cdot\mathbf{P}(\mathbf{r}'))\mathbf{r}'\}d\mathbf{r}'$$

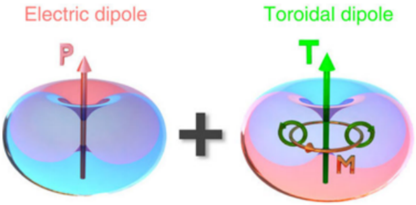
Miroshnichenko A. E. et al., Nature communications 6 (2015): 8069

Scattering cross-section (considering multipole moments up to the electric octupole moment)

$$\sigma_{\rm sca} \simeq \frac{k_0^4}{6\pi\varepsilon_0^2|\mathbf{E}_{inc}|^2}\left|\mathbf{p} + \frac{ik_0\varepsilon_d}{c}\mathbf{T}\right|^2 + \frac{k_0^4\varepsilon_d\mu_0}{6\pi\varepsilon_0|\mathbf{E}_{inc}|^2}|\mathbf{m}|^2 + \frac{k_0^6\varepsilon_d}{720\pi\varepsilon_0^2|\mathbf{E}_{inc}|^2}\sum|Q_{\alpha\beta}|^2 + \frac{k_0^6\varepsilon_d^2\mu_0}{80\pi\varepsilon_0|\mathbf{E}_{inc}|^2}\sum|M_{\alpha\beta}|^2 + \frac{k_0^8\varepsilon_d^2}{1890\pi\varepsilon_0^2|\mathbf{E}_{inc}|^2}\sum|O_{\alpha\beta\gamma}|^2.$$

Evlyukhin A. B. et al., Physical Review B. 94.20 (2016): 205434

Toroidal dipole moment



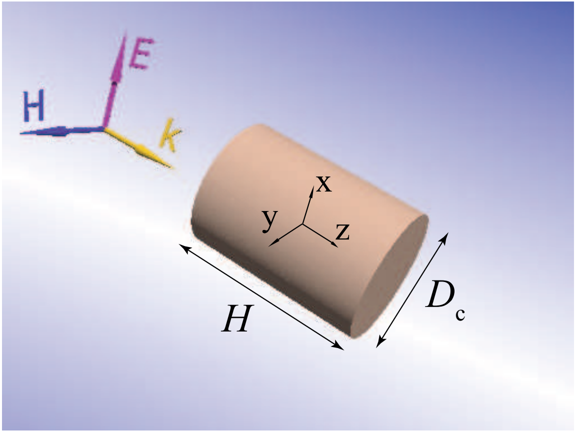
In the terms of irreducible representation of Cartesian multipoles toroidal dipole moment is a term which is separated from symmetrized and traceless magnetic quadrupole and electric octupole moments. It has the same far-field radiation pattern as electric dipole moment and can interfere with it constructively and destructively.

Miroshnichenko A. E. et al., Nature communications 6 (2015): 8069

Resonant forward scattering of light by high refractive-index dielectric nanoparticles with toroidal dipole contribution

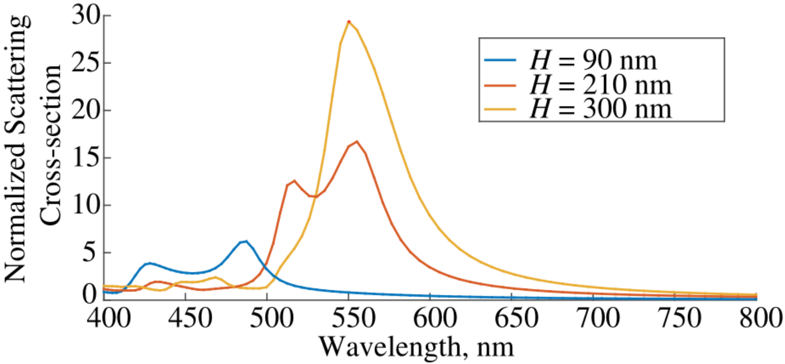
Terekhov P.D. et al., 'Resonant forward scattering of light by high-refractive-index dielectric nanoparticles with toroidal dipole contribution', *Optics Letters 42:4. 835-838 (2017).*

Considered System

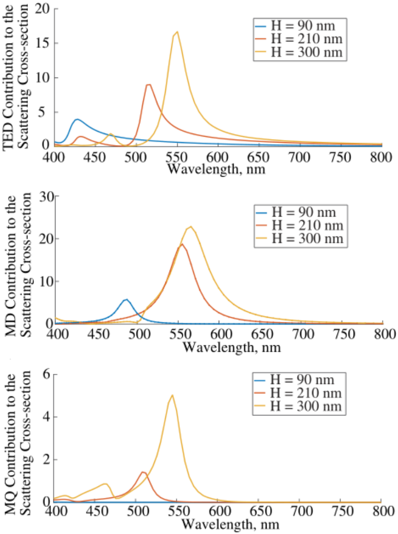


H = 90 - 300 nm, D_c = 100 nm.
λ = 400 - 800 nm.

Scattering cross-section of nanocylinders with different H



TED, MD and MQ Evolution with height increasing

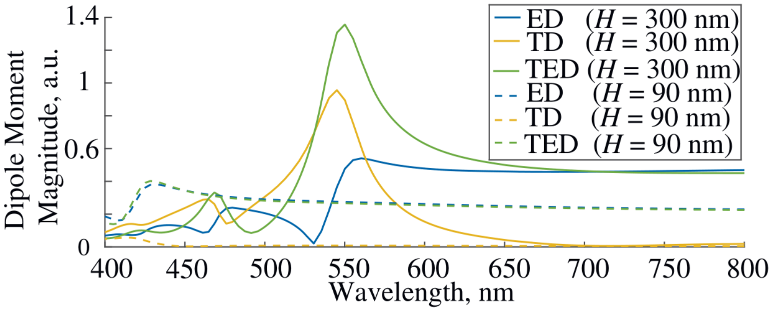


The separated development of multipoles contributions to the scattering cross section for dielectric nanocylinder with respect to height increasing.

$H = 90$, 210 and 300 nm,

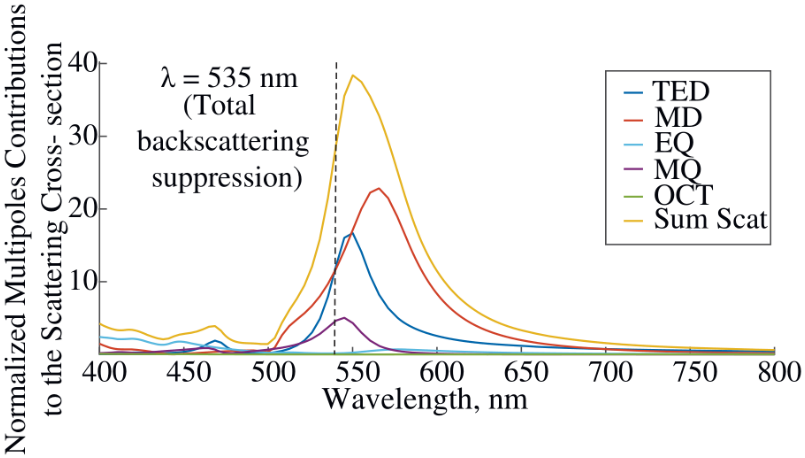
$D_c = 100$ nm.

Spectra of the absolute values of TED, ED, and TD

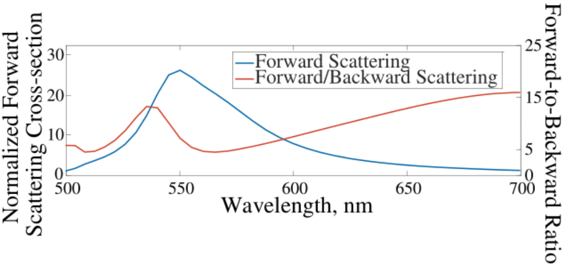


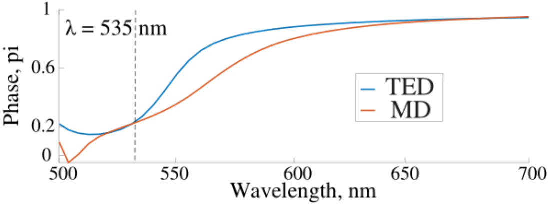
$H = 90$ and 300 nm, $D_c = 100$ nm.

Multipole contributions to the scattering cross-section



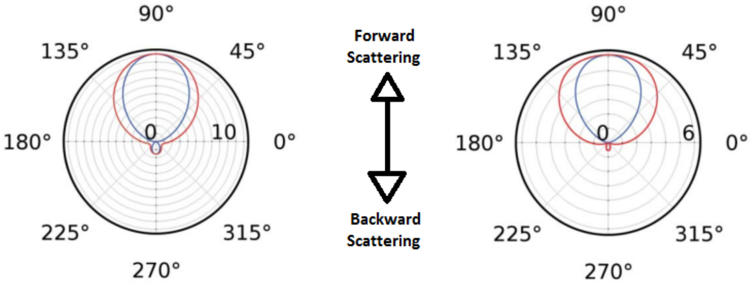
Forward/Backward Scattering and TED & MD Phases





$H = 300$ nm
$D_c = 100$ nm

Radiation Patterns



Radiation pattern at the maximum scattering wavelength

Radiation pattern at the maximum forward/backward scattering wavelength (**Kerker effect**)

Cylindrical nanoparticle, $H = 300$ nm, $D_c = 100$ nm.

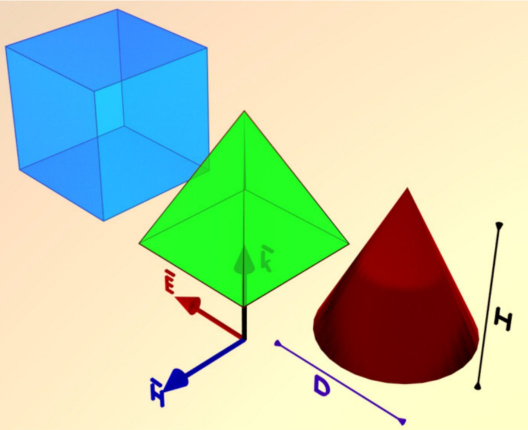
Summary on resonant forward scattering

- Constructive interference between toroidal and electric dipole moments of the nanoparticle can be realized in silicon nanoparticles
- Total electric dipole moment with dominant contribution of the toroidal dipole is resonantly excited in the nanoparticles and so called super-dipole mode is numerically demonstrated
- Due to the interference between electromagnetic fields generated by the total electric dipole and magnetic dipole moments of the nanoparticles, the Kerker-type effect (backward scattering suppression) can be numerically shown

Optical multipole resonances of non-spherical silicon nanoparticles and the influence of illumination direction

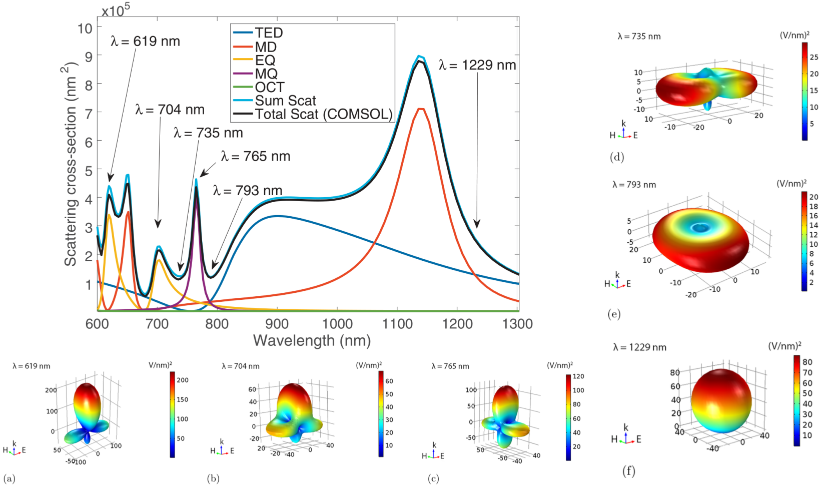
Terekhov P.D. et al., 'Multipolar response of non-spherical silicon nanoparticles in the visible and near-infrared spectral ranges',
Physical Review B 96, 035443 (2017)

Nanoparticles of different shape

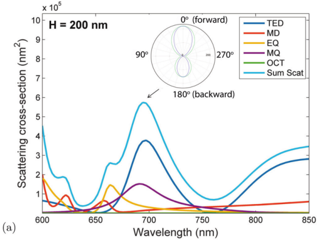


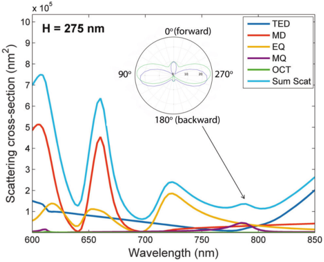
Parallelepiped, pyramid, and cone with varying height H and diameter of D = 250 nm.

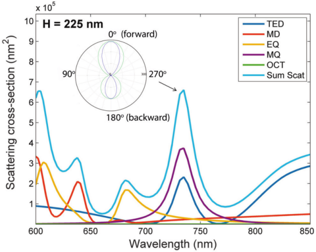
Multipole contributions to the scattering cross-section



Scattering cross-section of nanoparalelepipeds

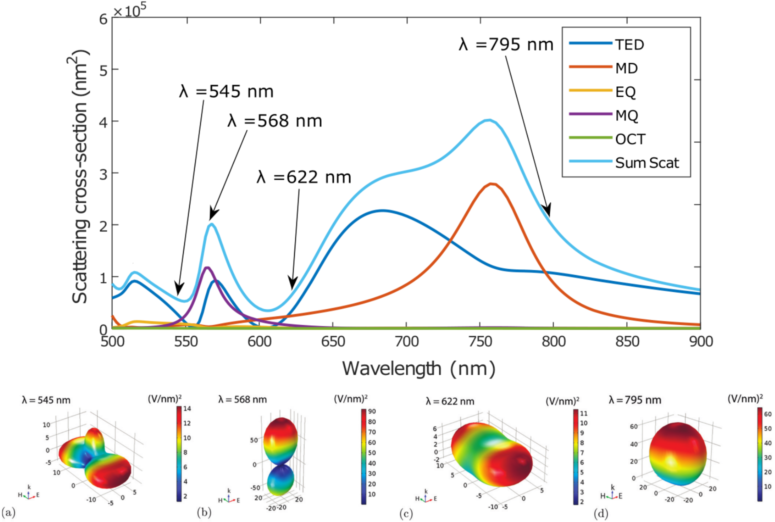




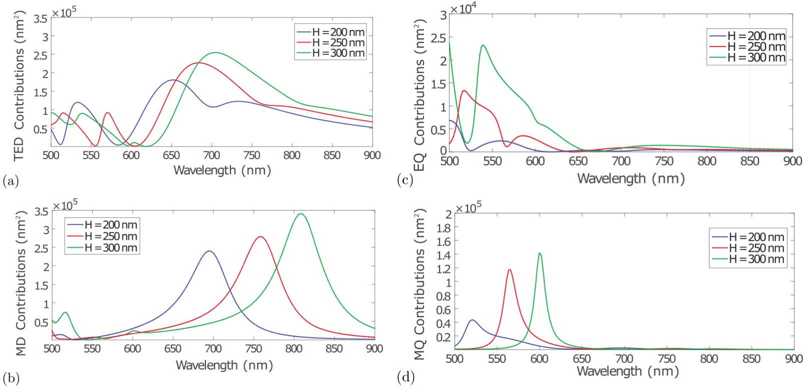


For parallelepipedal nanoparticles with changed height separated MQ resonance dissapares and becames merged with TED resonance. If we increase the height of the particle, the resonant region becames non-resonant and provides side-scattering type of radiation pattern.

Multipole Decomposition of SCS of nanopyramid

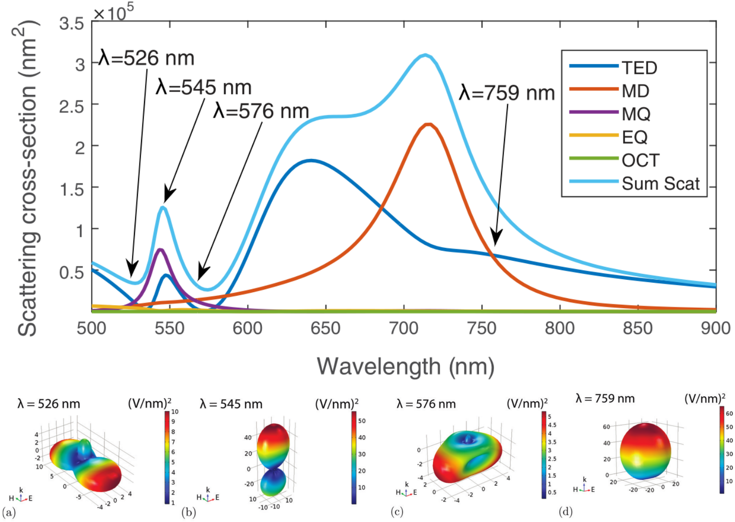


Influence of the particle height

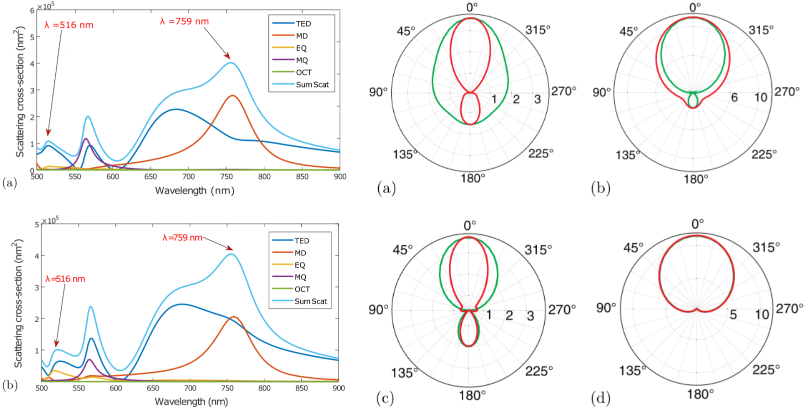


Evolution of multipole resonances with changing the height of nanopyramid.

Multipole decomposition of SCS of Si nanocone



Unsymmetry effect in nanopyramid scattering



2D scattering patterns: the incidence (a,b) from the pyramid base, $\lambda = 516$ nm and 759 nm, ((c,d) from the pyramid top,$\lambda = 516$nm and 759 nm. Red (green) contour corresponds to the plane of the incident E (H) polarization.

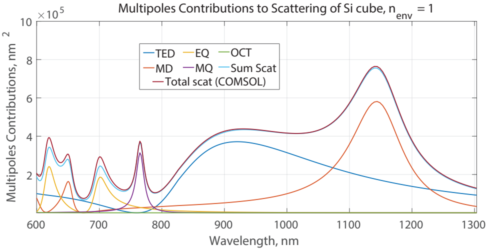
Summary on multipole excitations in Si nanoparticles

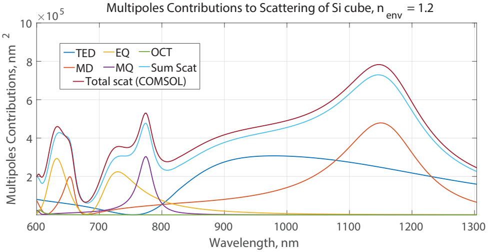
- Multipoles up to the third order that were excited by light in parallelepipedal, pyramidal, and conical silicon nanoparticles were investigated.
- Peculiar scattering patterns (even side-scattering) with certain predominant scattering directions can be obtained by tuning the spectral overlap of several multipoles.
- It has been shown that the effect of the asymmetrical multipole response in conical and pyramidal particles depends on the illumination direction.
- Our investigation provides important information about the roles of the high order multipoles in the light scattering by nonspherical nanoparticles and can be applied for the development of the nanoantennas, metasurfaces, coatings etc.

Influence of surrounding media refractive index

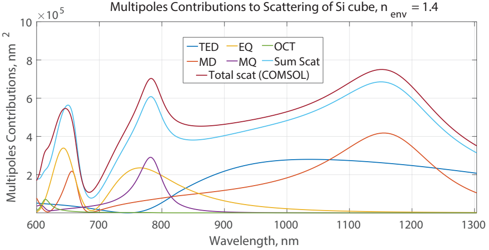
Terekhov P.D. et al., 'Wideband forward-scattering effect and multipoles evolution in media' *(In preparation)*

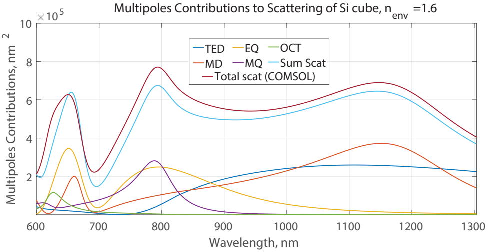
Multipole decomposition of SCS for n = 1 and n = 1.2



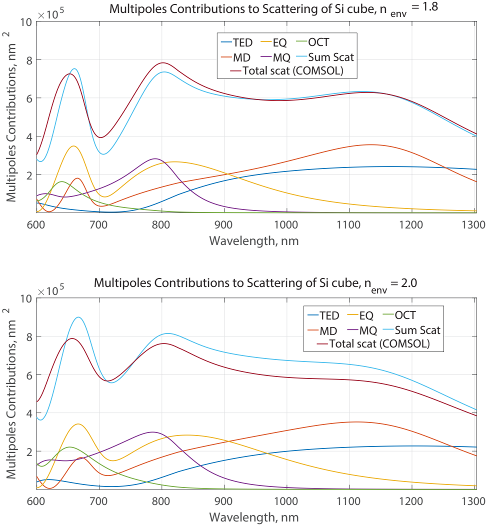


Multipole decomposition of SCS for n = 1.4 and n = 1.6

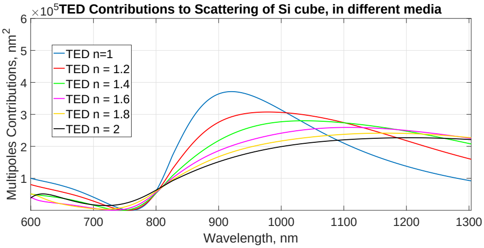


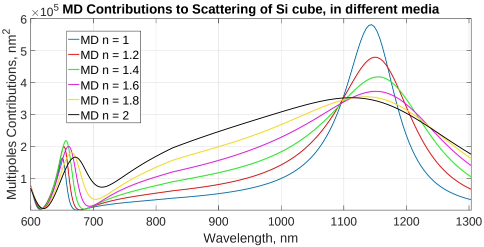


Multipole decomposition of SCS for n = 1.8 and n = 2

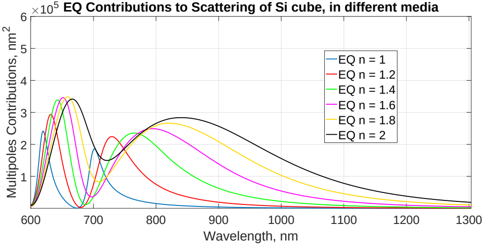


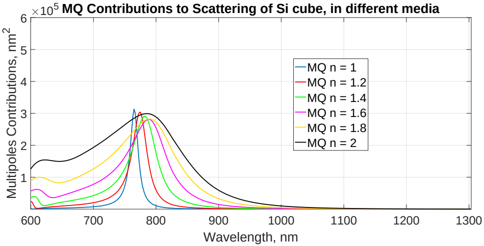
Evolution of dipole moments as n changes.



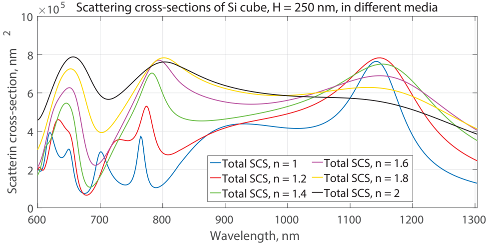


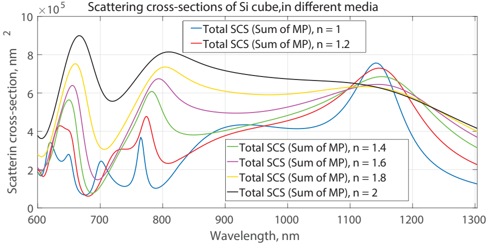
Evolution of quadrupole moments as n changes.



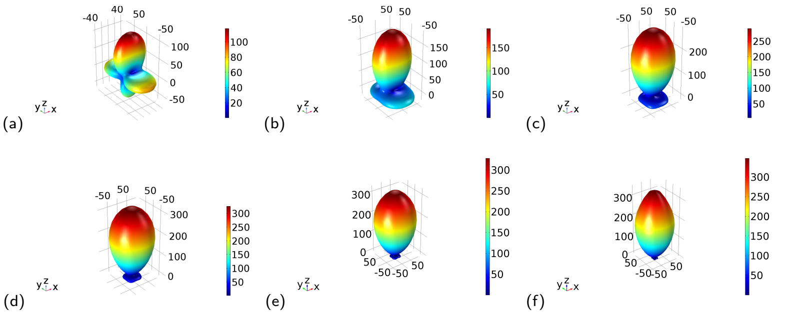


Evolution of Scattering cross-section as *n* changes.



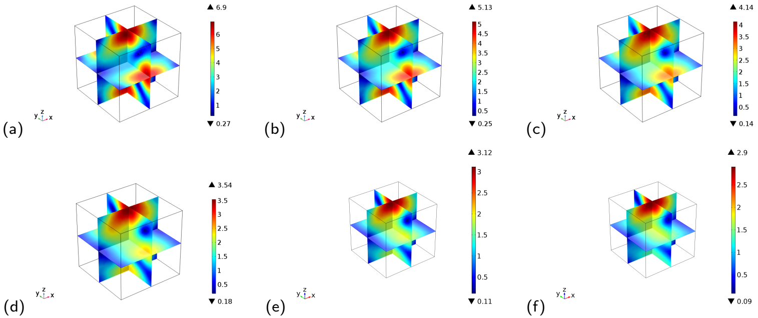


3D radiation patterns in the area of MQ resonance



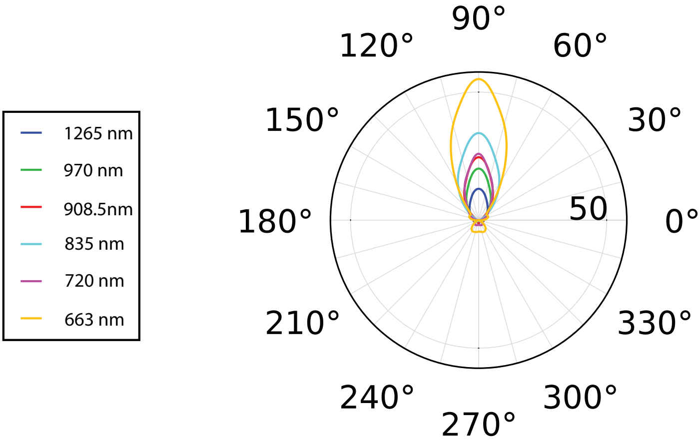
Radiation patterns for (a) $n_{env} = 1$, $\lambda = 765nm$ (b) $n_{env} = 1.2$, $\lambda = 775nm$ (c) $n_{env} = 1.4$, $\lambda = 783nm$ (d) $n_{env} = 1.6$, $\lambda = 789nm$ (e) $n_{env} = 1.8$, $\lambda = 789nm$ (f) $n_{env} = 2$, $\lambda = 789nm$.

3D current distributions in the area of MQ resonance



Electric field distribution inside the nanocube for (a) $n_{env} = 1$, $\lambda = 765nm$ (b) $n_{env} = 1.2$, $\lambda = 775nm$ (c) $n_{env} = 1.4$, $\lambda = 783nm$ (d) $n_{env} = 1.6$, $\lambda = 789nm$ (e) $n_{env} = 1.8$, $\lambda = 789nm$ (f) $n_{env} = 2$, $\lambda = 789nm$.

2D radiation patterns in n = 2 media for several λ



2D radiation patterns in n = 2 media for λ mentioned in the legend.

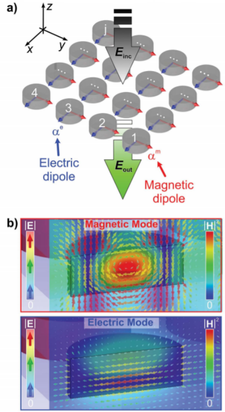
Conclusions

- Directly calculated scattering cross-sections are close to the sum of multipole contributions, but there is some difference for high-index surroundings.
- Electric multipole moments (TED, EQ) experience stronger red-shift than magnetic multipole moments (MD, MQ).
- Separated scattering cross-section peaks transform to smoother merged peaks as n rises; separated MQ and EQ resonances are not longer exist for high-index media.
- Overal scattering cross-section of Si Cube increses as n rises.
- Multipole decomposition method can be applied for non-air media.
- For high-index media amplification of broadband forward scattering amplification takes place.
- Current distributions inside the nanocube concentrates in the forward part of the particle as n rises.

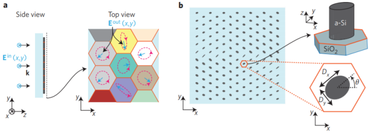
Multipole analysis of periodic metasurfaces and engineering of broadband absorption

Terekhov P.D. et al., 'All-dielectric metasurfaces engineered absorption' *(In preparation)*

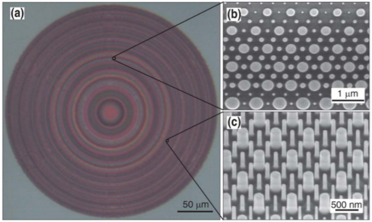
Possible Applications



Decker M. et al. **'High-Efficiency Dielectric Huygens Surfaces'** Advanced Optical Materials 3.6 (2015): 813-820

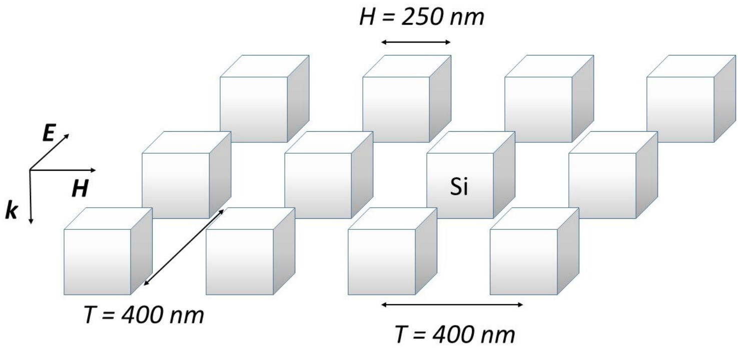


Arbabi A. et al. **'Dielectric metasurfaces for complete control of phase and polarization with subwavelength spatial resolution and high transmission.'** Nature nanotechnology 10 (2015): 937-942



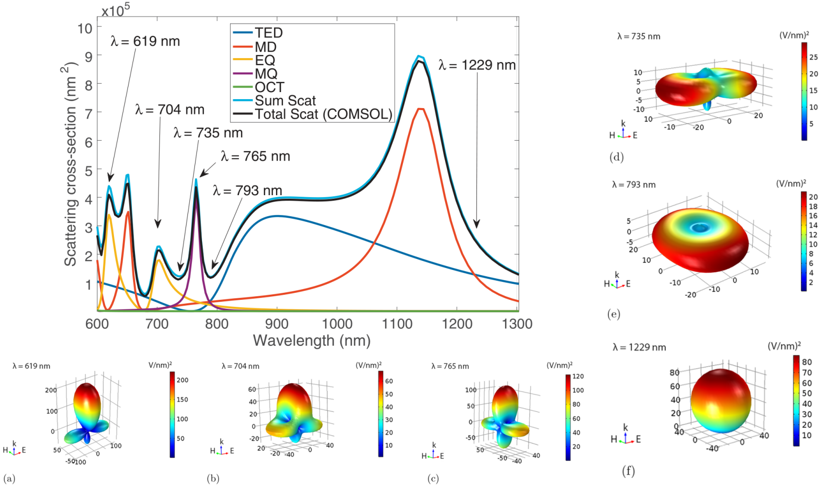
Arbabi E. et al. **'Multiwavelength polarization-insensitive lenses based on dielectric metasurfaces with meta-molecules.'** Optica 3.6 (2016): 628-633

Considered System



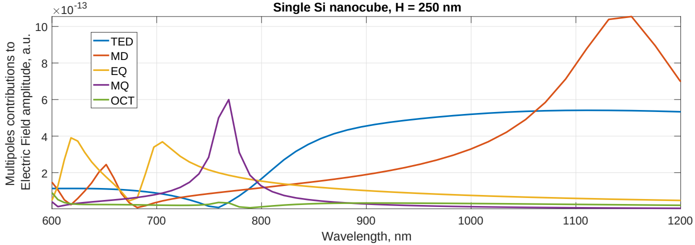
In this work we study silicon metasurface based on cubic meta-atoms when 1) metasurface surrounded by air and 2) metasurface is located on the glass substrate

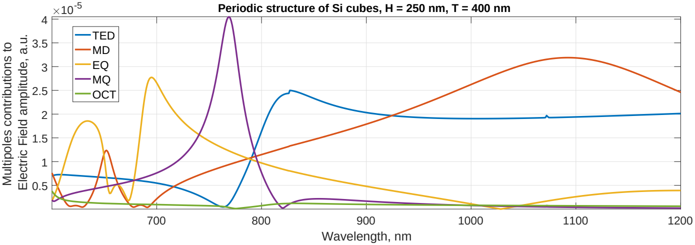
Multipole contributions to the scattering cross-section



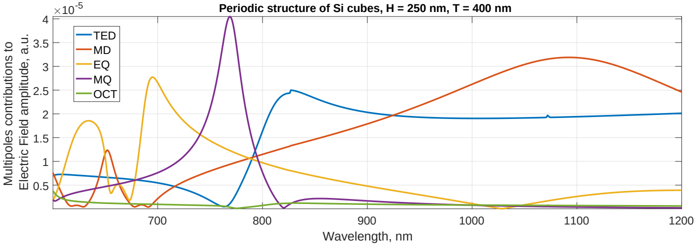
Terekhov P. D. et al., Physical Review B 96, 035443 (2017)

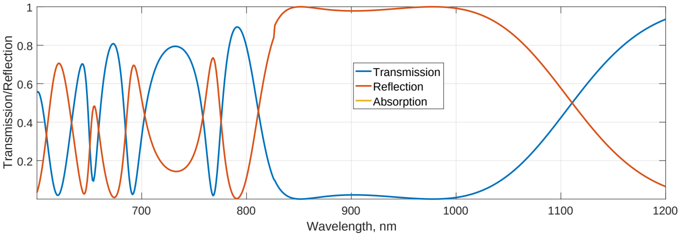
Single cube vs array of cubes



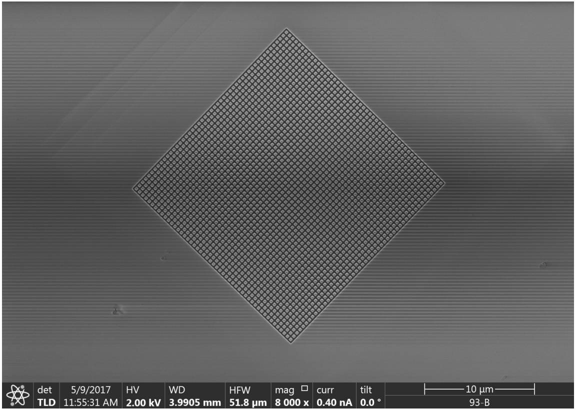


Connection to the transmission spectra



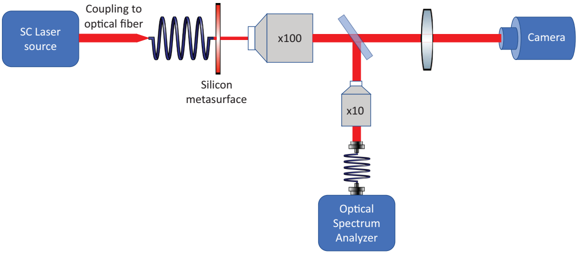


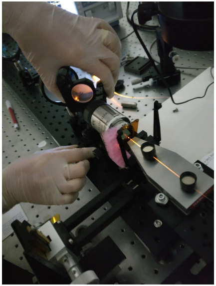
Metasurface imaging



SEM image of fabricated metasurface.

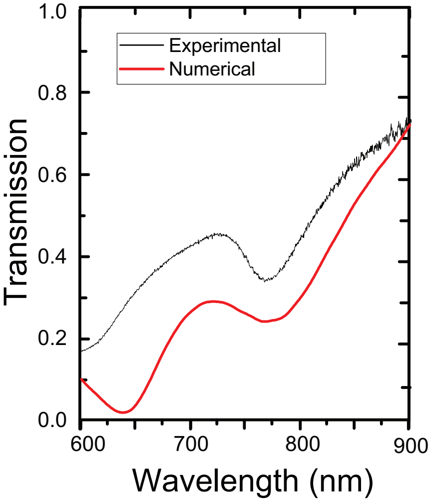
Proof of concept of experiment





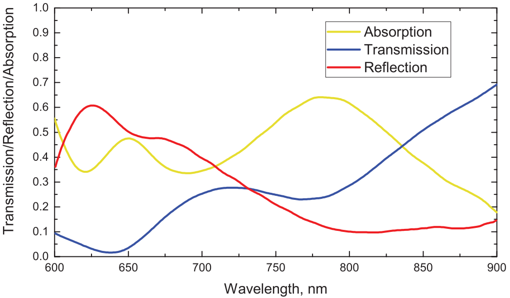
Schematics of the experimental setup (left) and photograph of the constructed setup (right).

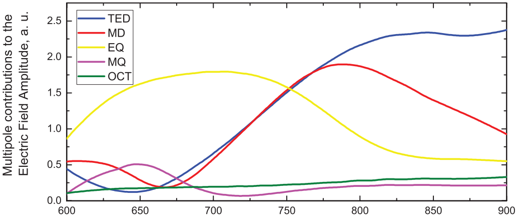
Experiment - Modelling comparison of transmission



Transmission spectra: experimental (black) and calculated (red).

Multipole analysys of the metasurface on substrate





According to multipole decomposition, the presented reflection peak corresponds to the area of predominating EQ resonance, and the dip in transmission can be associated with the absorption peak; this peak can be associated with MD resonance excitation. Multipole decomposition has been performed using the similar method as for single nanoparticle in the air.

Summary on dielectric metasurfaces research

- Silicon metasurface created based on single particle investigations have been studied.
- Multipoles contribution to electric field amplitudes was compared for 1) single cube and 2) array of cubes.
- Si metasurface on bk7 substrate have been investigated numerically and experimentally.
- Multipole decomposition of currents in the meta-atoms of metasurface on substrate have been performed.
- EQ and MD resonance areas are associated with the reflection and absorption peaks correspondingly.

Our works

The research described in this talk is summarised in my recent publications:

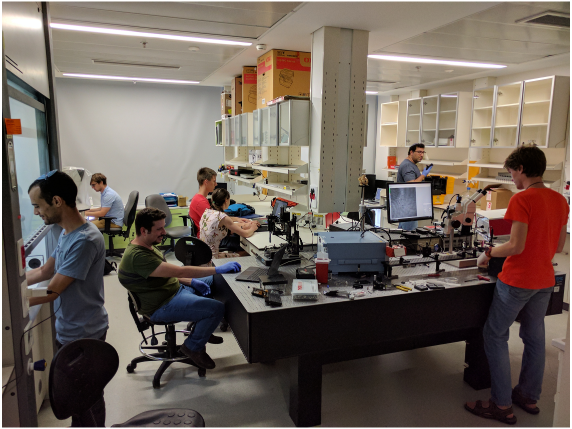
1. **Terekhov P. D.** et al. 'Resonant forward scattering of light by high-refractive-index dielectric nanoparticles with toroidal dipole contribution', *Optics Letters* 42:4. 835-838 (2017).
2. **Terekhov P. D.** et al. 'Multipolar response of non-spherical silicon nanoparticles in the visible and near-infrared spectral ranges', *Physical Review B* 96, 035443 (2017).
3. **Terekhov P. D.** et al. 'All-dielectric metasurfaces engineered absorption' *(In preparation)*
4. **Terekhov P. D.** et al.'Wideband forward-scattering effect and multipoles evolution in media' *(In preparation)*

To be continued

Currently I am doing my research in Ben-Gurion University and ITMO University under the joint supervision of Dr. Alina Karabchevsky (BGU) and Dr. Alexander Shalin (ITMO). We are exploring interesting directions of the research described, such as:

- Influence of non-air medium on multipoles excitation.
- Enhanced light-matter interaction as with plasmonic nanoantenas reported by *A. Karabchevsky et al, Nature Light Sci&Appl. 5, e16164 (2016)*, but using all-dielectric nanoantennas as alternative.
- Coupling of two resonant systems: All-dielectric resonator to molecular resonator which may be described by high order multipole moments (*A. Karabchevsky and A. Kavokin, Nature Sci Rep 6:1-7 (2016)*).
- Optical properties of all-dielectric metasurfaces which support high-order multipole excitation.

Our Team



Our team in Ben-Gurion University of Negev.
Thanks for your attention!

Multipoles' expressions

$$\mathbf{p} = \int \mathbf{P}(\mathbf{r}')d\mathbf{r}' \tag{1}$$

$$\mathbf{m} = -\frac{i\omega}{2}\int [\mathbf{r}' \times \mathbf{P}(\mathbf{r}')]d\mathbf{r}' \tag{2}$$

$$\mathbf{T} = \frac{i\omega}{10}\int \{2\mathbf{r}'^2\mathbf{P}(\mathbf{r}') - (\mathbf{r}' \cdot \mathbf{P}(\mathbf{r}'))\mathbf{r}'\}d\mathbf{r}' \tag{3}$$

$$Q = 3\int [\mathbf{r}'\mathbf{P}(\mathbf{r}') + \mathbf{P}(\mathbf{r}')\mathbf{r}' - \frac{2}{3}(\mathbf{r}' \cdot \mathbf{P}(\mathbf{r}'))\hat{U}]d\mathbf{r}' \tag{4}$$

$$M = \frac{\omega}{3i}\int \{[\mathbf{r}' \times \mathbf{P}(\mathbf{r}')]\mathbf{r}' + \mathbf{r}'[\mathbf{r}' \times \mathbf{P}(\mathbf{r}')]\}d\mathbf{r}' \tag{5}$$

Evlyukhin A. B. et al., Physical Review B. 94.20 (2016): 205434