Light-on-a-Chip Group
Electrooptical Engineering

ITMO UNIVERSITY BGU

Excitation of high-order multipoles in Si metasurface

Pavel Terekhov[1,2], Kseniia Baryshnikova [2], A. I. Kuznetsov[3], Y. H. Fu[3], Andrey Evlyukhin [2,4], Alexander Shalin [2], Alina Karabchevsky [1]

[1]Ben-Gurion University, Israel
[2]ITMO University, Russia
[3]Data Storage Institute, Singapore
[4]Laser Zentrum Hannover e.V., Germany

terekhovpd@gmail.com

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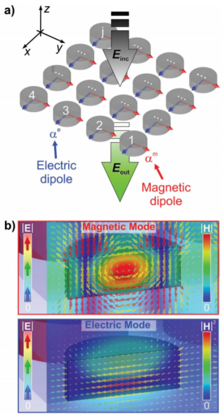
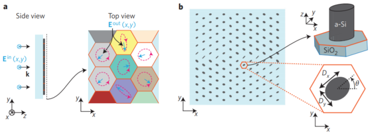
Outline

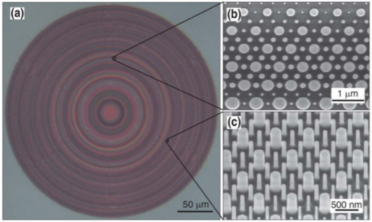
Possible Applications



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

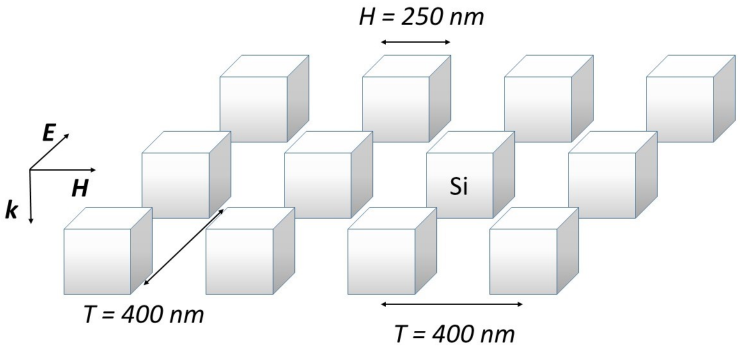


Arbabi A. et al. **'Dielectric metasurfaces for complete control of phase and polarization with subwavelength spatial resolution and high transmission.'** Nature nanotechnology 10 (2015): 937-942



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 both in air medium and on glass substrate.

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**

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

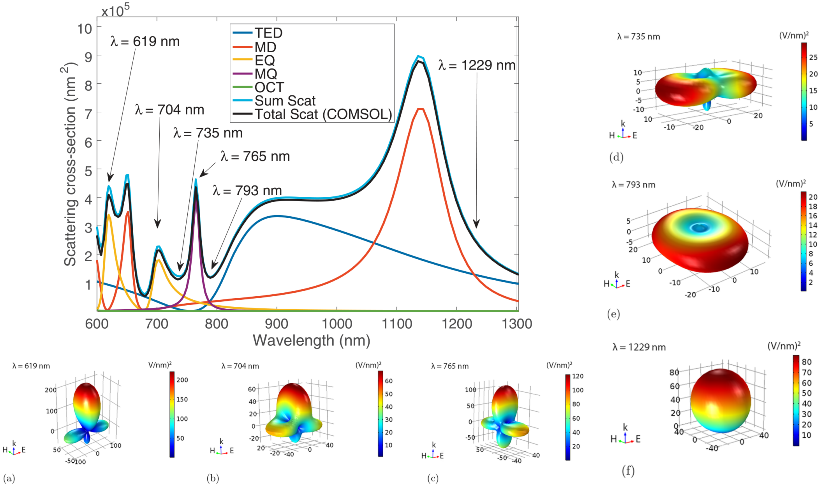
Miroshnichenko A. E. et al., Nature communications 6 (2015): 8069

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

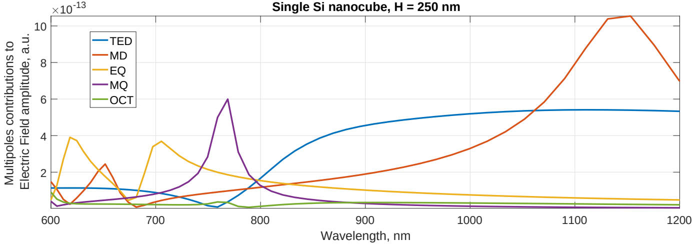
$$\sigma_{\rm sca} \simeq \frac{k_0^4}{6\pi\varepsilon_0^2|\mathbf{E}_{inc}|^2}|\mathbf{p} + \frac{ik_0\varepsilon_d}{c}\mathbf{T}|^2 + \frac{k_0^4\varepsilon_d\mu_0}{6\pi\varepsilon_0|\mathbf{E}_{inc}|^2}|\mathbf{m}|^2 + \frac{k_0^6\varepsilon_d}{720\pi\varepsilon_0^2|\mathbf{E}_{inc}|^2}\sum|Q_{\alpha\beta}|^2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

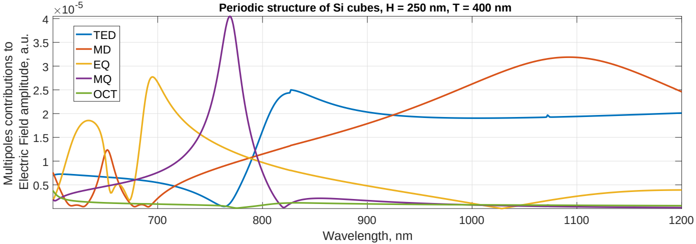
Evlyukhin A. B. et al., Physical Review B. 94.20 (2016): 205434

Multipole contributions to the scattering cross-section

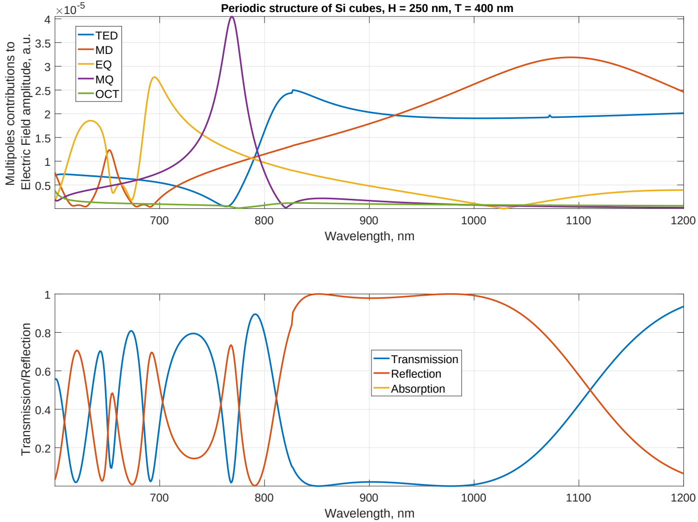


Comparison of multipole decompositions

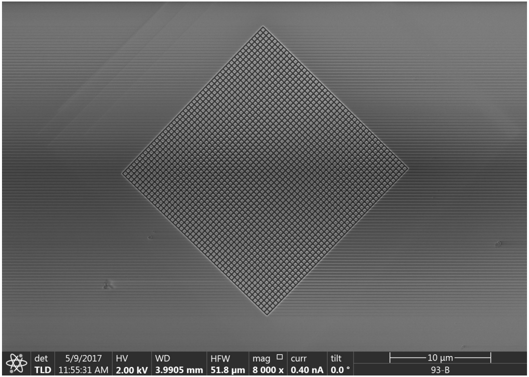


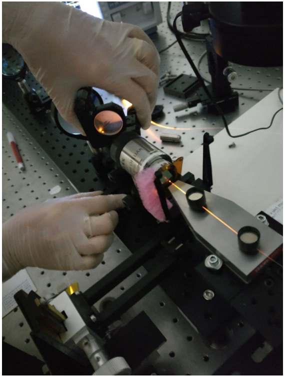


Connection to the transmission spectra



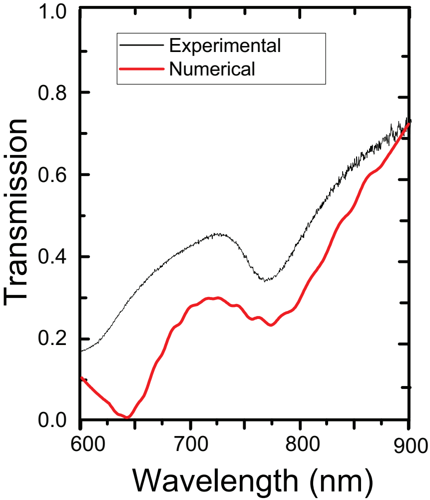
Moving to experimental studying





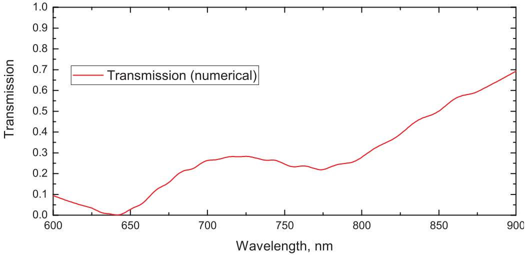
The fabricated sample and created experimental setup for the transmission measurements. Silicon metasurface have been fabricated using the FIB technique.

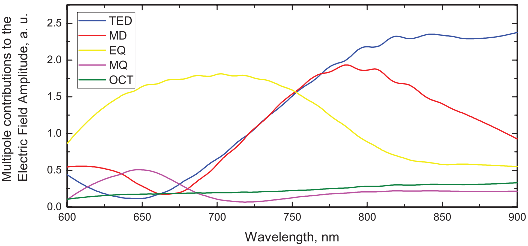
Experiment - Modelling comparison of transmission



After characterizing the fabricated structure we performed a numerical modelling accordingly to the expected metasurface parameters (material dispersion, thin film thickness and so on). Obtained results presents the similar peak and dip in transmission. Now we can attempt to analyze the structure using the multipole decomposition technique (currents integration over one meta-atom and their decomposition).

Multipole analysys of the metasurface on substrate





According to executed multipole decomposition, the presented transmission peak corresponds to the area of predominating EQ resonance, and the gap in transmission can be connected to the interference between TED, MD and EQ multipole moments. Multipole decomposition have been performed using the similar method as for single nanoparticle in the air.

Summary

- Silicon metasurface created based on single particle investigations have been studied.
- Multipole decomposition of single Si nanocube and periodic structure based on such meta-atoms have been compared.
- 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.

Published and in preparation

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

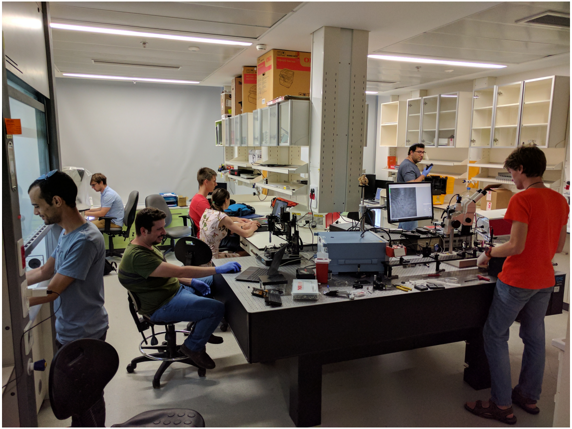
1. **Terekhov P. D.** et al. 'Resonant forward scattering of light by high-refractive-index dielectric nanoparticles with toroidal dipole contribution', *Optics Letters* 42:4. 835-838 (2017).
2. **Terekhov P. D.** et al. 'Multipolar response of non-spherical silicon nanoparticles in the visible and near-infrared spectral ranges', *Physical Review B* 96, 035443 (2017).
3. **Terekhov P. D.** et al. 'Excitation of high-order multipoles in Si metasurface based on parallelepipedal meta-atoms' (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)*).
- Continuation of studying of 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