Полупроводниковые метаповерхности для нелинейной фотоники

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Полупроводниковые метаповерхности для нелинейной фотоники и оптических аналоговых вычислений

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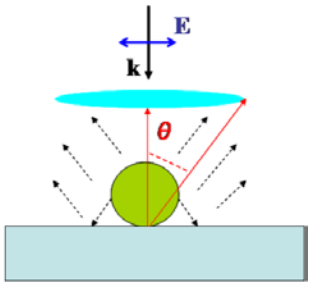
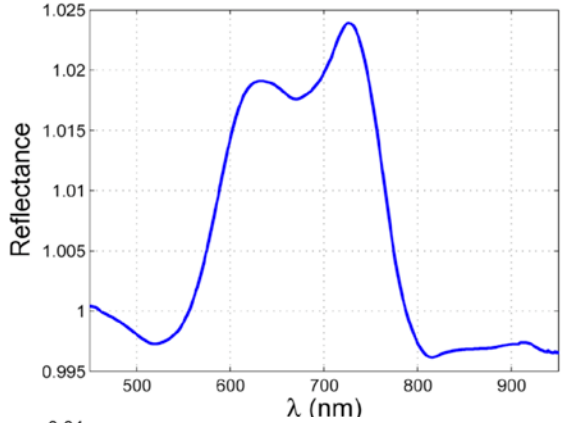
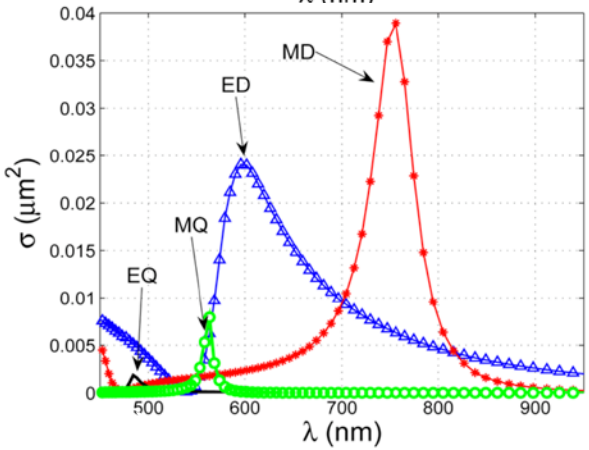
Mie scattering. Basics



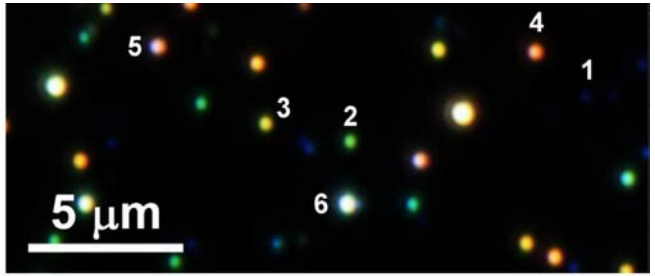
$$\mathbf{E}(\mathbf{r}) = \frac{k_0^2 e^{ik_0 r}}{4\pi\varepsilon_0 r}([\mathbf{n}\times[\mathbf{p}\times\mathbf{n}]] + \frac{ik_0}{6}[\mathbf{n}\times[\mathbf{n}\times\hat{Q}\mathbf{n}]] + \frac{1}{c}[\mathbf{m}\times\mathbf{n}] + \frac{ik_0}{2c}[\mathbf{n}\times(\hat{M}\mathbf{n})])$$

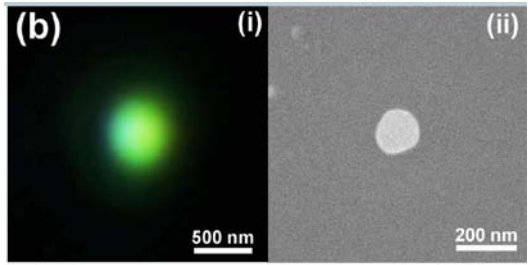
A.B. Evlyukhin et al.,
Nano Letters **12**, 3749 (2012)

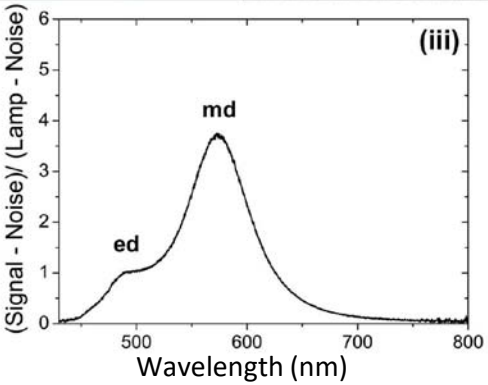




Mie-type resonances in high-index nanoparticles

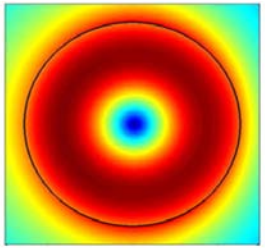




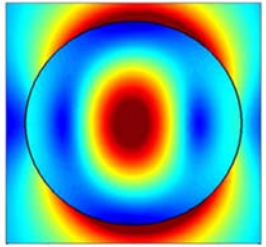


$|E|^2$ maps

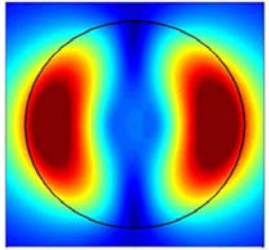
(1) Magnetic dipolar



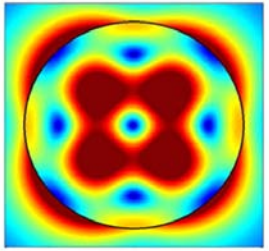
(2) Electric dipolar



(3) Magnetic quadrupolar

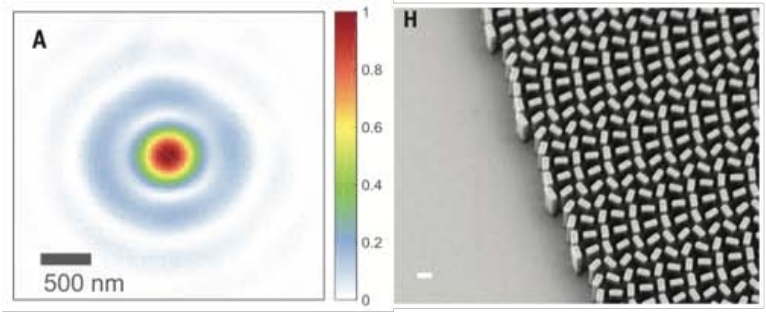


(4) Electric quadrupolar

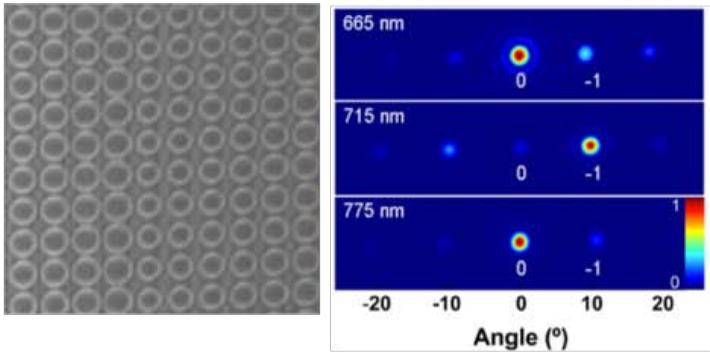


Kuznetsov et al.,
Sci. Rep. **2**, 492 (2012)

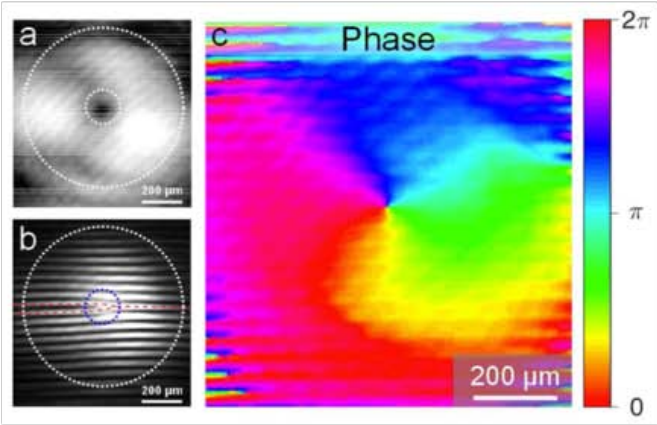
All-dielectric photonic metasurfaces



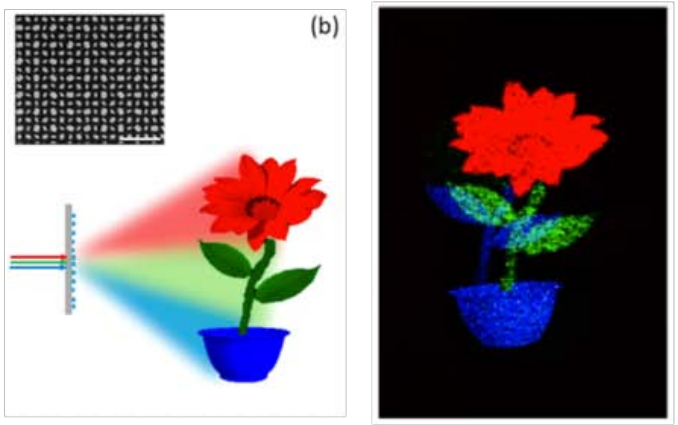
M. Khorasaninejad et al., Science 352, 1190 (2016)



Y. F. Yu et al., Las. Phot. Rev. 9, 412 (2015)



K. Chong et al., Nano Lett. 15, 5369 (2015)



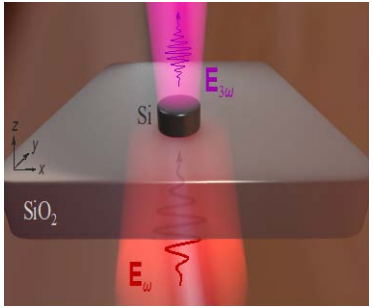
B. Wang et al., Nano Lett. 16, 5235 (2016)

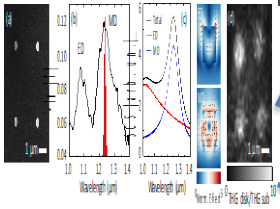
Nonlinear optics of Mie-resonant nanoparticles

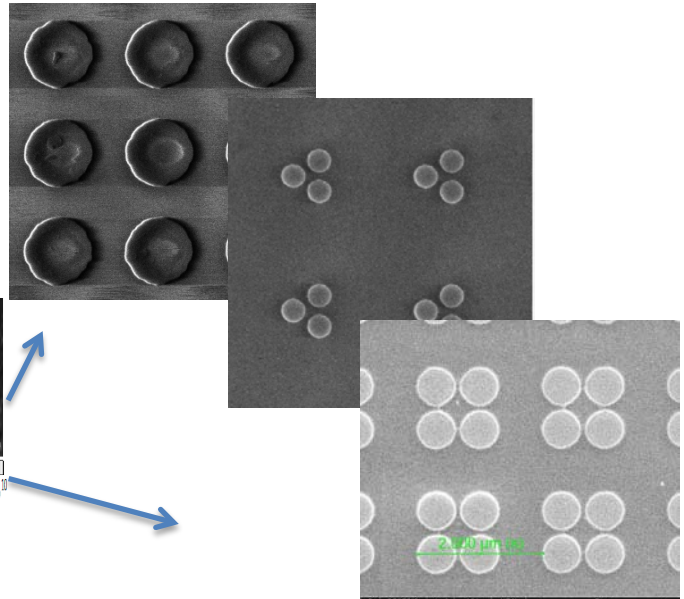
Goals:

- small values of $\chi^{(2)}$ and $\chi^{(3)}$
- small volumes
- no phase matching

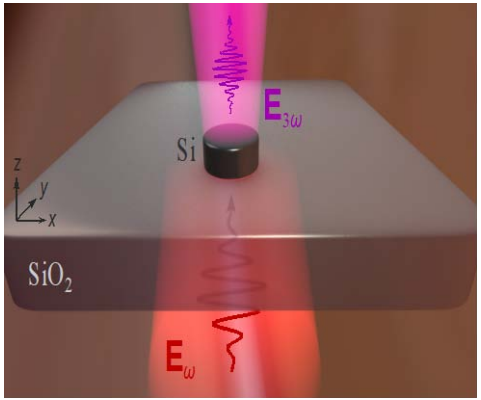
- Nonlinear optical enhancement
- Magnetic vs. electric resonances
- Coupled nanoparticles: oligomers and metasurfaces

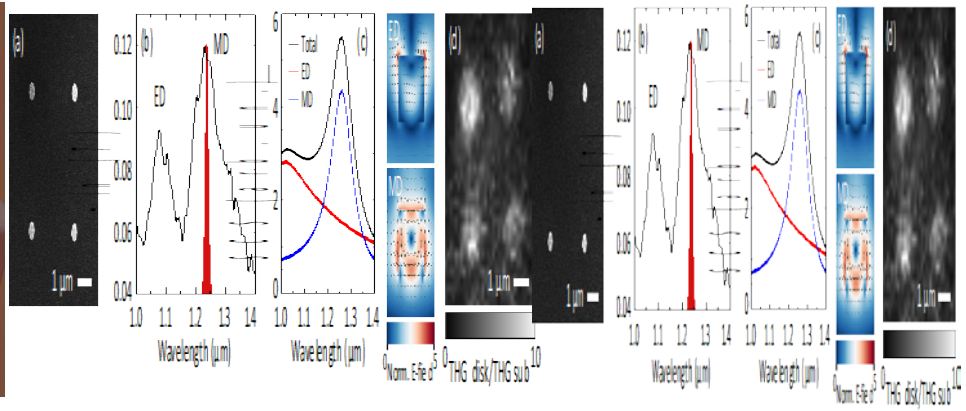


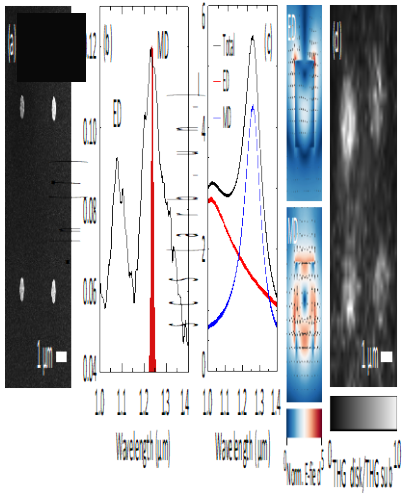


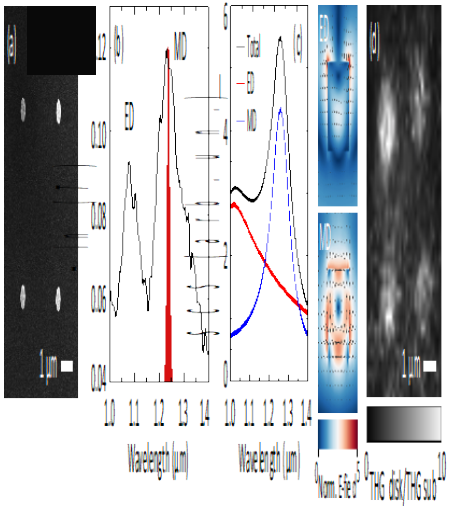


Third-harmonic generation confocal microscopy





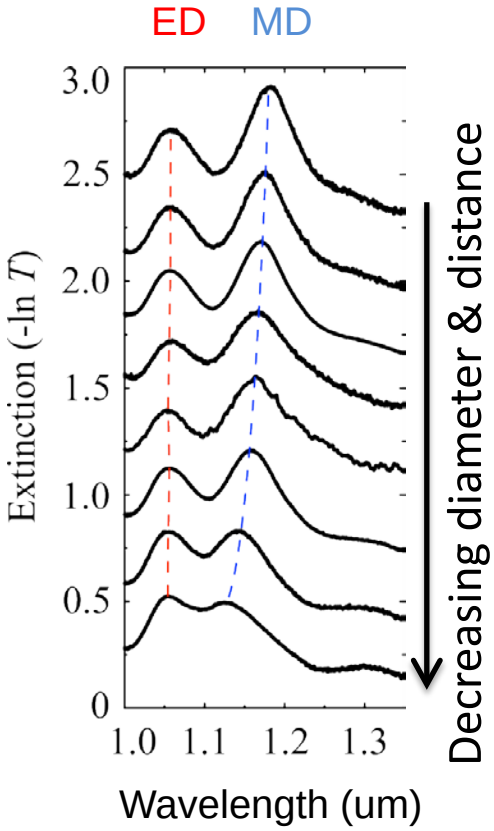


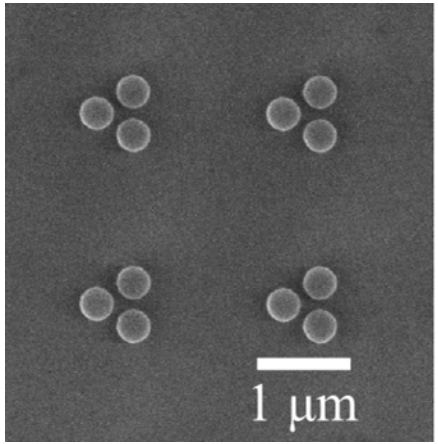


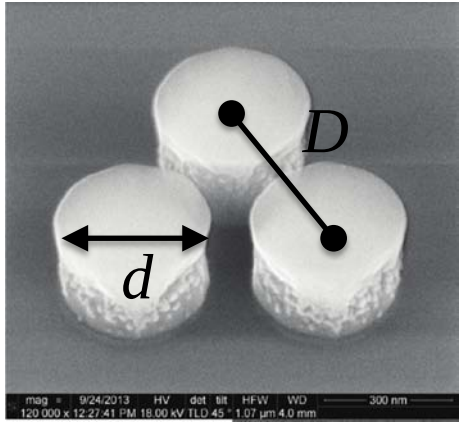
Olympus FluoView FV1000
+ Coherent Chameleon Ultra II
+ Coherent OPO pump @ 1240 nm

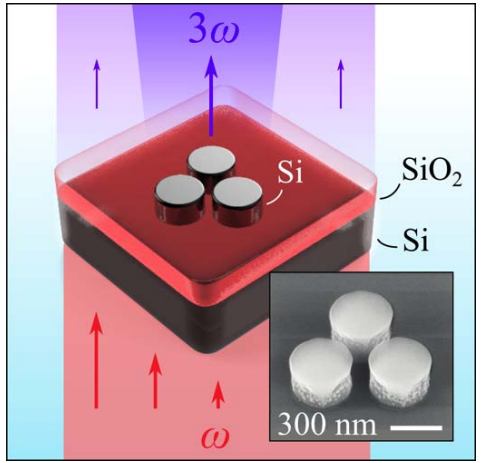
Nano Letters **14**, 6488 (2014)

Silicon nanodisk trimers sample design







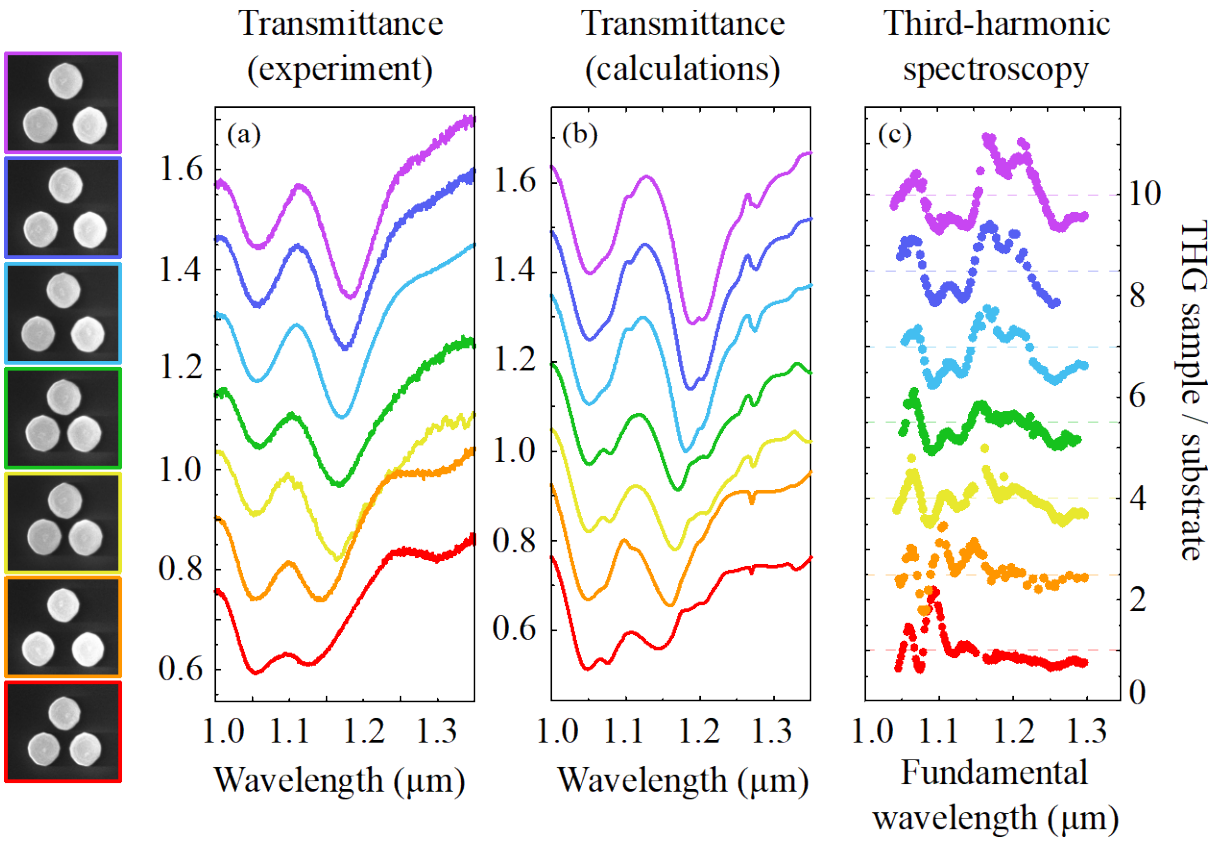


Different *d* and *D* sets:

d = 350—375 nm

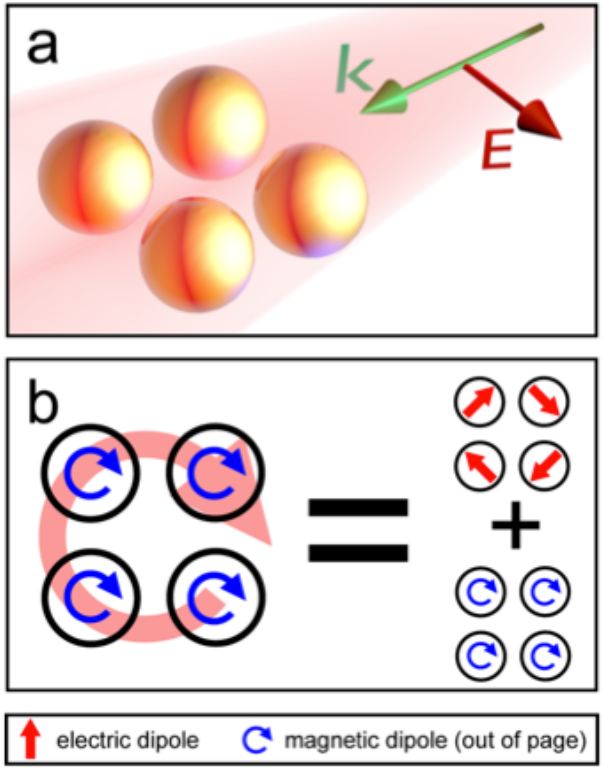
D = 460—560 nm

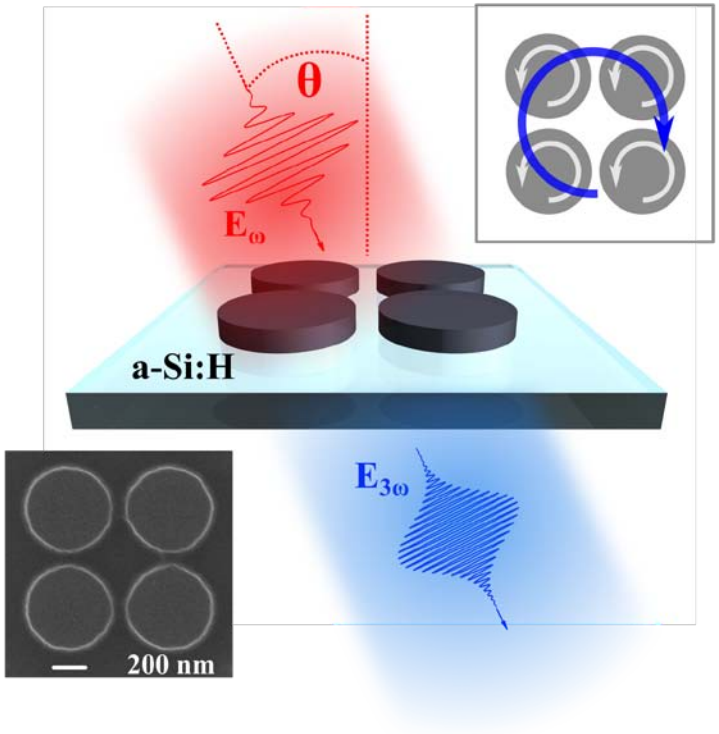
THG spectroscopy of silicon trimers



ACS Photonics **2**, 578 (2015)
Phil. Trans. R. Soc. A **375**, 20160281 (2017)

Quadrumers: optical retardation and collective resonance

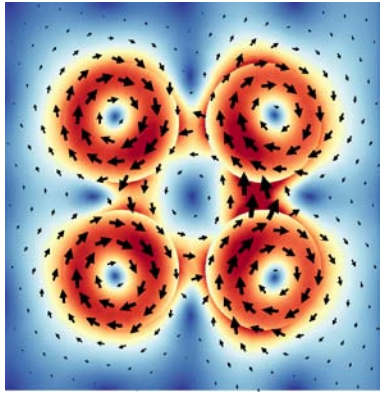


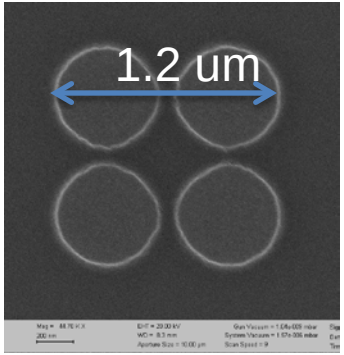


B. Hopkins et al., ACS Photonics 2, 724 (2015)

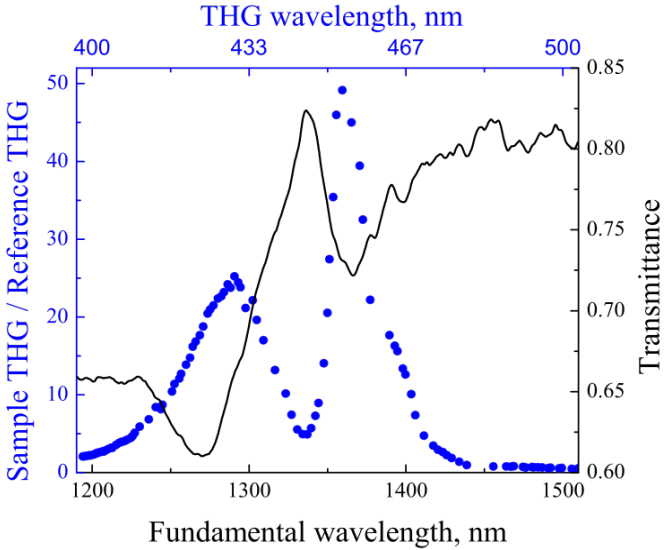
Nano Letters **16**, 4857 (2016)

THG enhancement at magnetic Fano resonance





- Amorphous silicon
- Resonance spectrum
  = spectrum of the pulse
- Low TH absorption

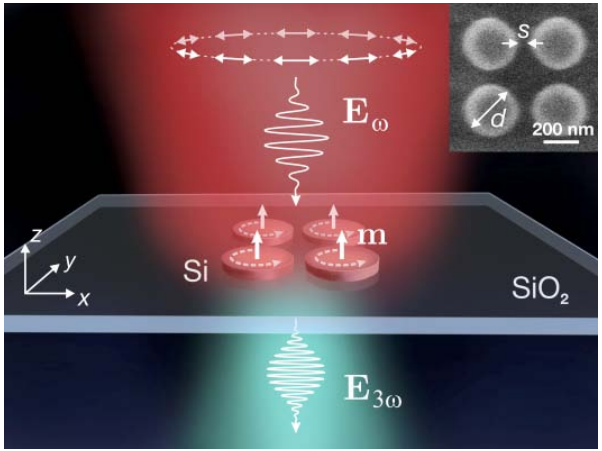


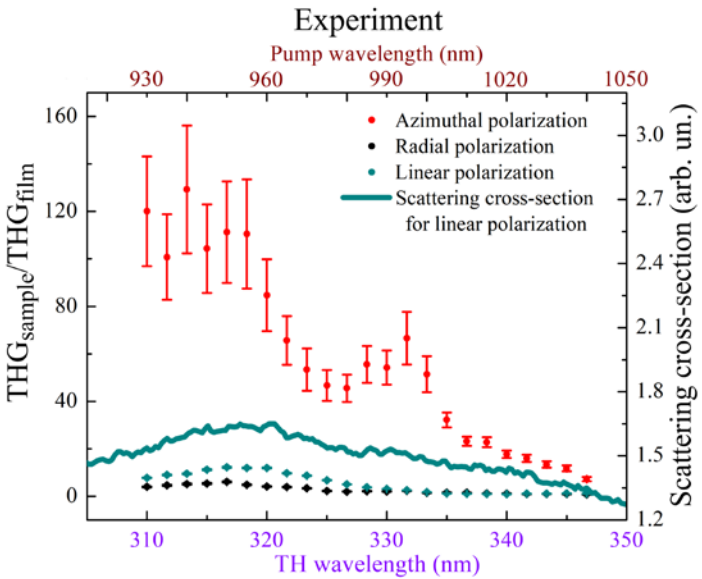
IR to blue conversion ~10^{-5}

Record set for
a silicon subwavelength object

Nano Letters **16**, 4857 (2016)
Nano Letters **20**, 3471 (2020)

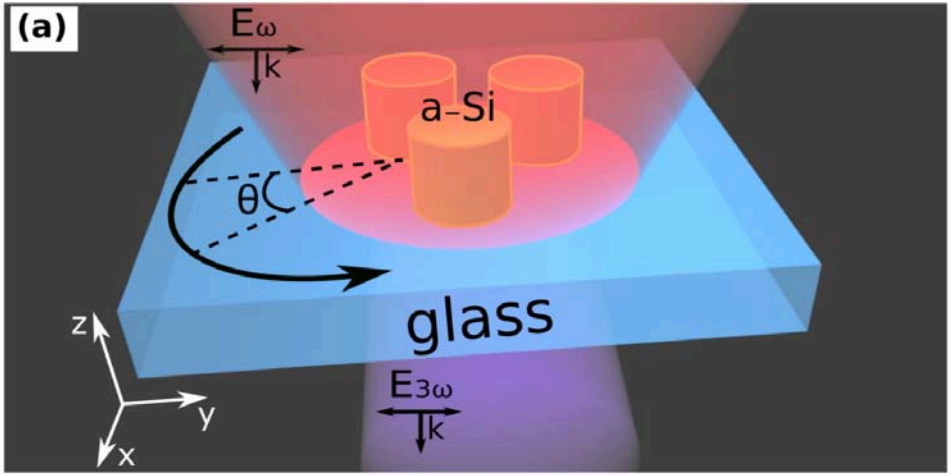
Enhanced Nonlinear Light Generation in Oligomers under Vector Beam Illumination

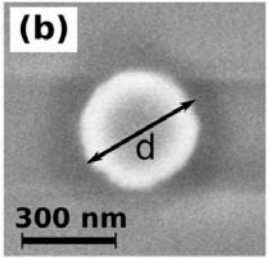


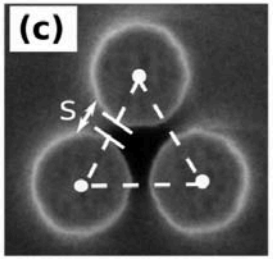


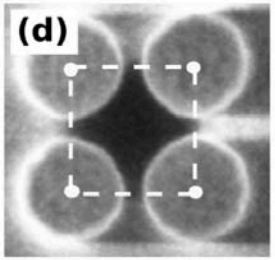
Nano Letters **20**, 3471 (2020)

Tailored nonlinear anisotropy in Mie-resonant dielectric oligomers









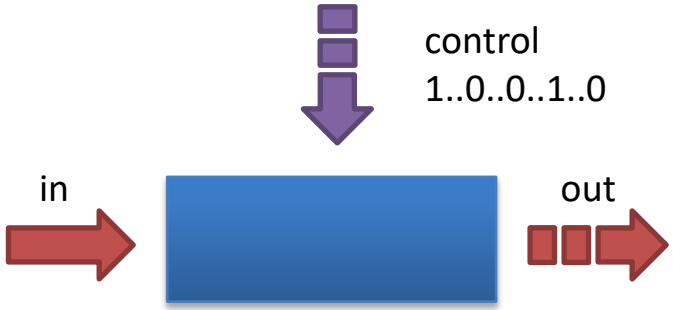
Idea:

- linear scattering remains isotropic

- azimuthal dependence of THG signal reflects their point-group symmetry

Adv. Optical Mater. **7**, 1900447 (2019)

All-optical switching by nanophotonic elements



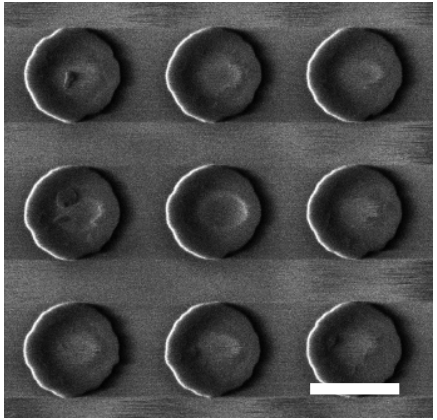
coherent approaches
— via wave mixing or other multiphoton processes
— no relaxation time

incoherent approaches
— via solid-state excitations
— relaxation time is a strong limiting factor

All-optical switching in Si and GaAs metasurfaces

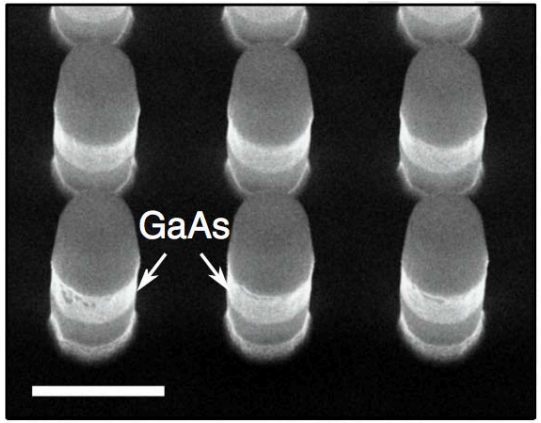
- Two-photon absorption enhancement observation in Mie-resonant Si metasurfaces
- Free-carrier-induced ultrafast tuning of direct band gap GaAs metasurface

silicon



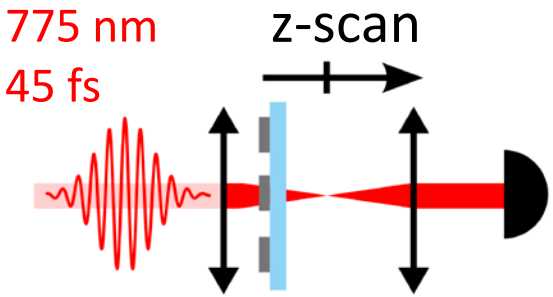
Nano Letters **15**, 6985 (2015)

gallium arsenide

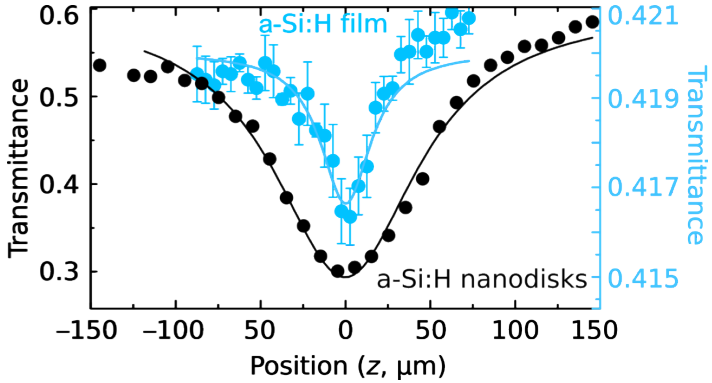


Nature Commun. **8**, 17 (2017)

Nonlinear absorption: Im $\chi^{(3)}(\omega = \omega + \omega - \omega)$. Silicon

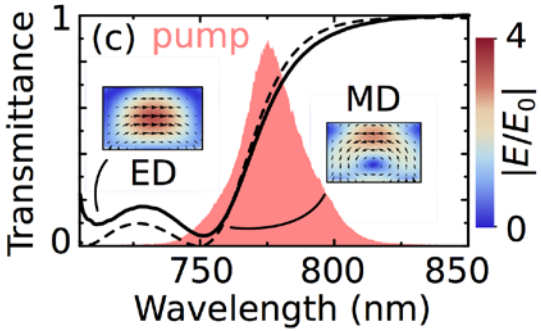


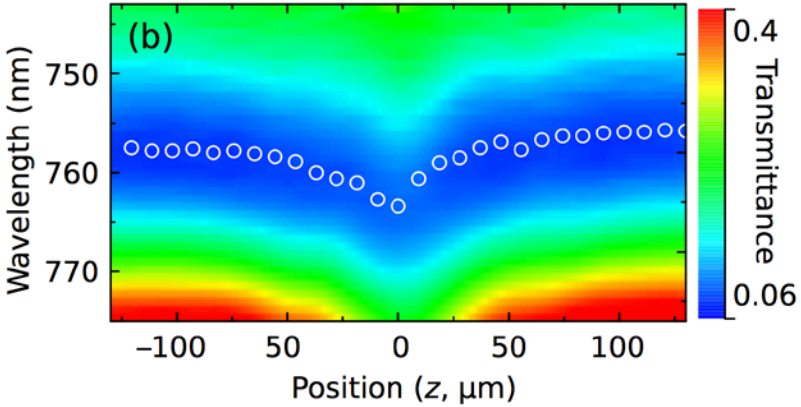
$$T(z) = 1 - \frac{1}{2\sqrt{2}} \frac{\beta_{\text{sam}} IL}{1 + \left(\frac{z}{z_0}\right)^2}$$



β_{film} = 0.07 cm/kW

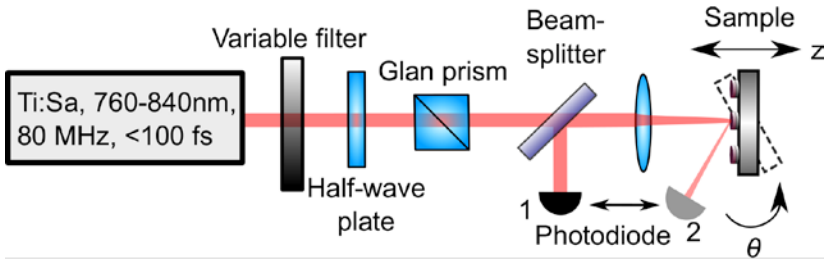
β_{sam} = 5.6 cm/kW (film x80)



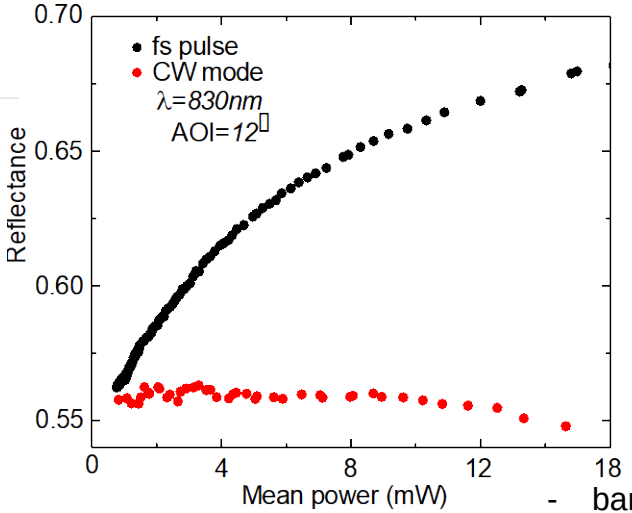


Nano Letters **15**, 6985 (2015)

Intensity dependent reflectance. Gallium Arsenide



FS pulse mode vs CW mode

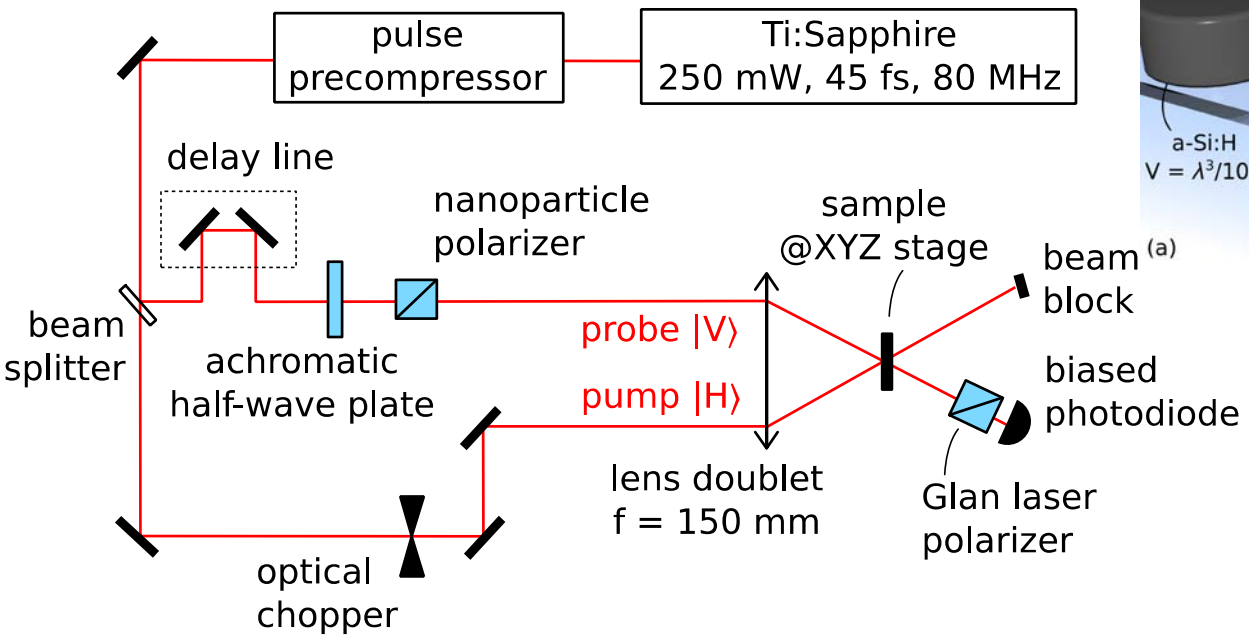


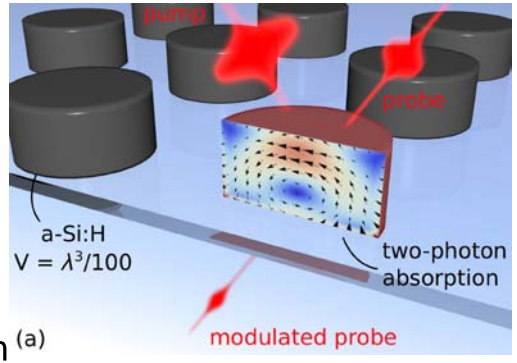
- band filling
- bandgap shrinkage
- Drude term

$$\uparrow I \;\square\; \uparrow N_{free\text{-}carr} \;\square\; \Delta\kappa, \Delta n$$

ACS Photonics **6**, 2797 (2019)

Frequency-degenerate pump–probe spectroscopy

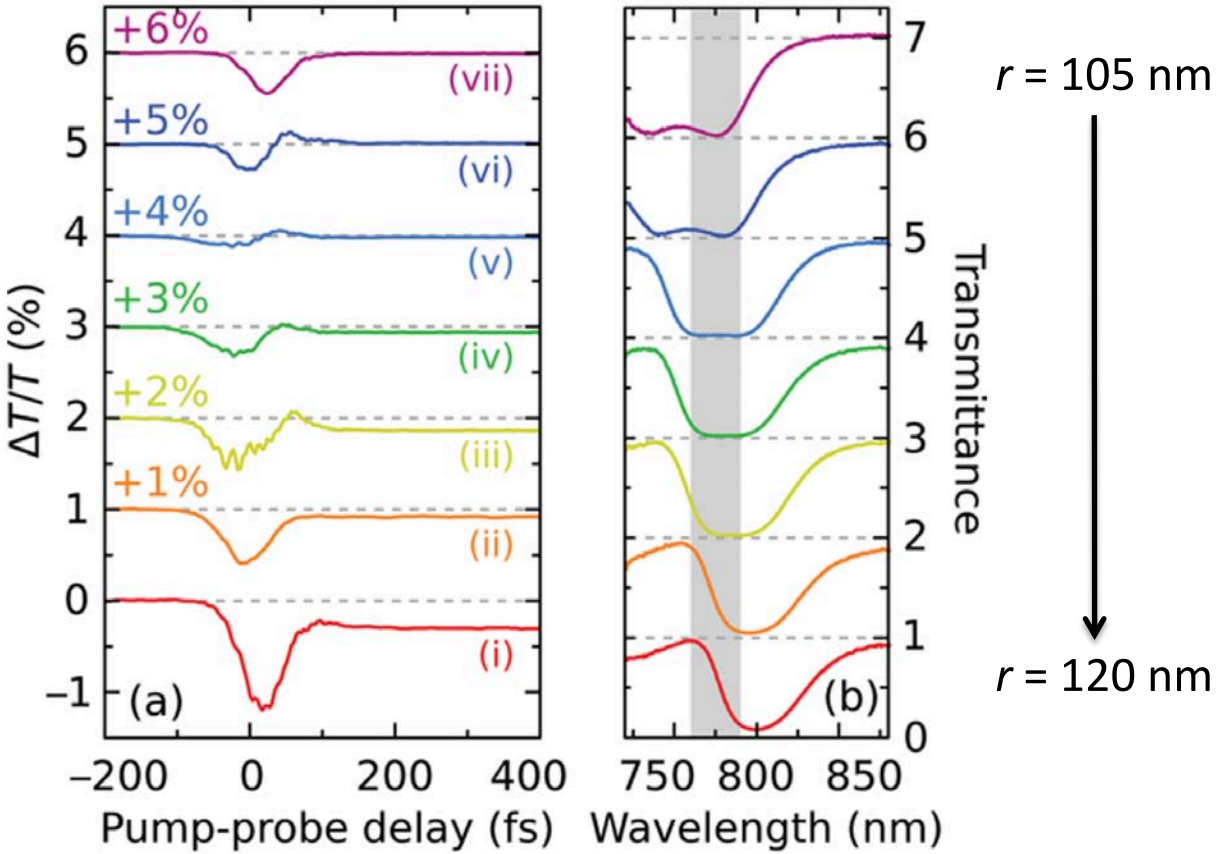




13 fJ per disk

Nano Letters **15**, 6985 (2015)

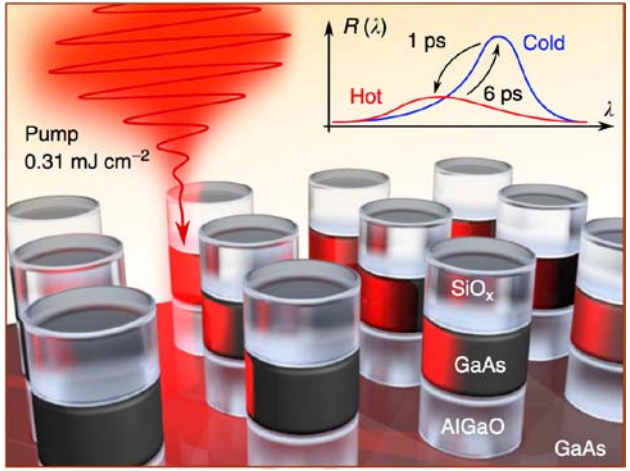
Frequency-degenerate pump–probe

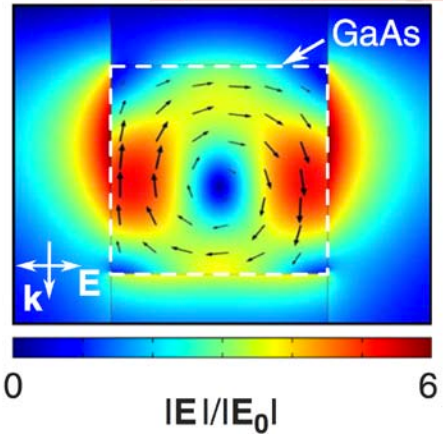


Nano Letters **15**, 6985 (2015)

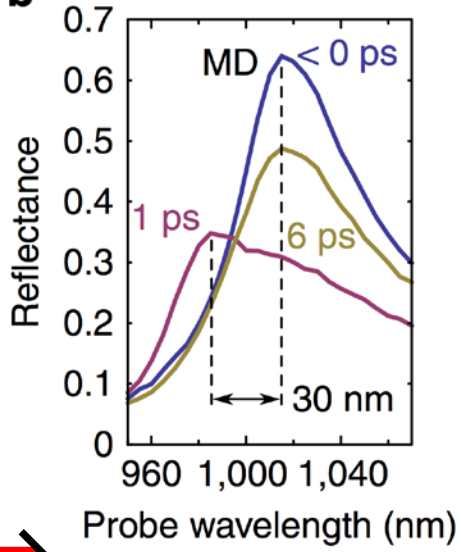
TPA spike with the FC dispersion eliminated

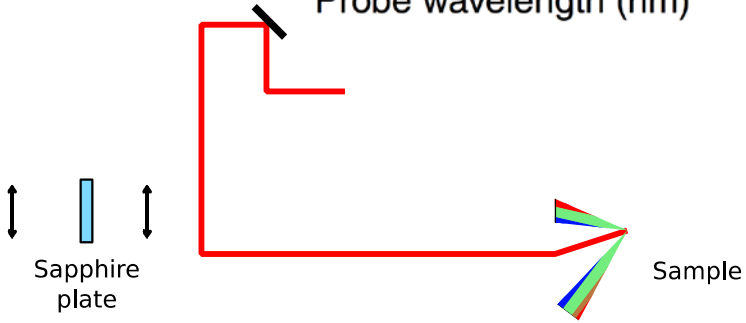
Pump-probe spectroscopy with supercontinium probe





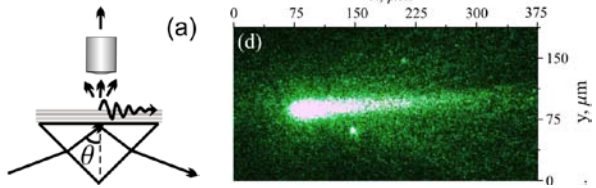
Nature Commun. **8**, 17 (2017)



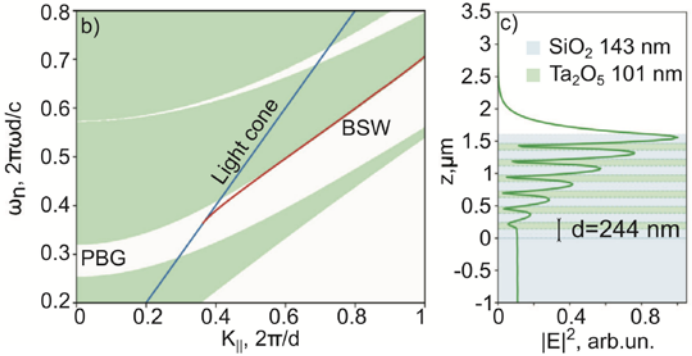


de

Bloch surface waves



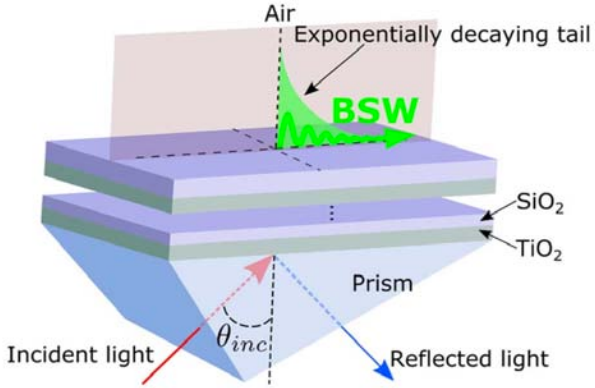
I. Soboleva et al. PRL **108,** 123901 (2012)

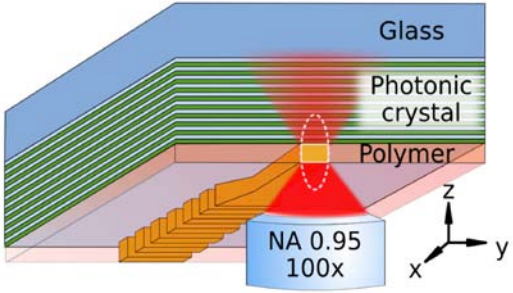


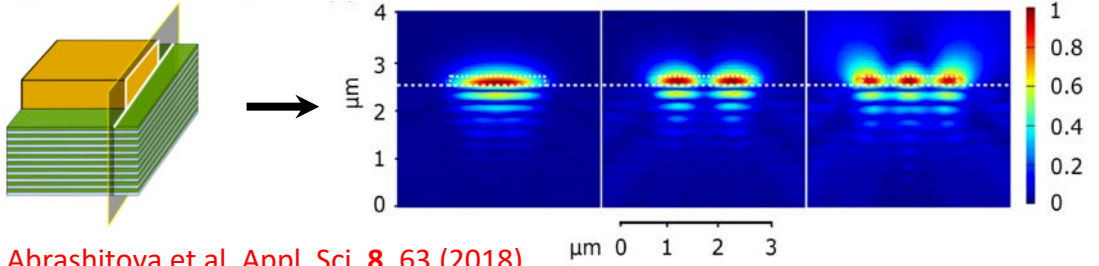
Applications of BSW:
- sensing
- enhancing light-matter interaction
- SERS
- optical manipulation
- **<u>integrated photonics</u>**

BSW waveguides on top of PC can be made of low-refractive-index materials

Two-photon lithography for printing single-mode and multimode BSW waveguides





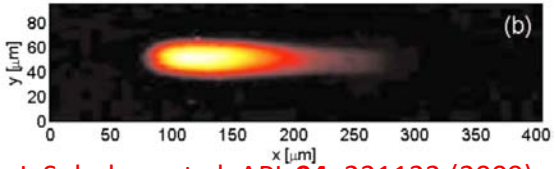


BSW advantages
- light localization on the surface
- no absorption
- long propagation distance (> cm in experiments)
- arbitrary spectral range (from UV to mid IR and THz)
- TE- and TM-polarized BSW
- narrow spectral and angular resonance
- wide variety of PC materials

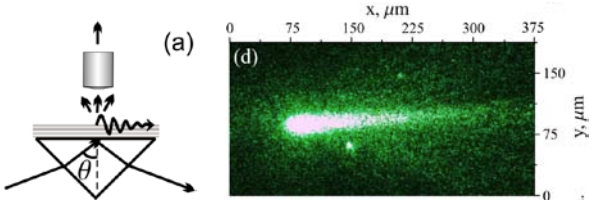
V. Koju, W. Robertson Opt. Lett. (2016)

K. Abrashitova et al. Appl. Sci. **8**, 63 (2018)

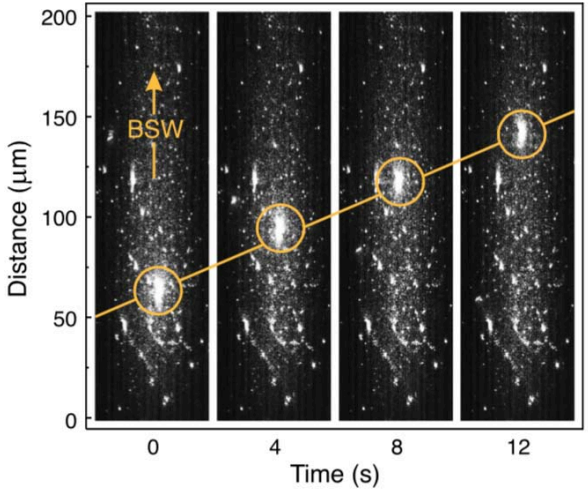
Bloch surface waves



I. Soboleva et al. APL **94,** 231122 (2009)



I. Soboleva et al. PRL **108,** 123901 (2012)

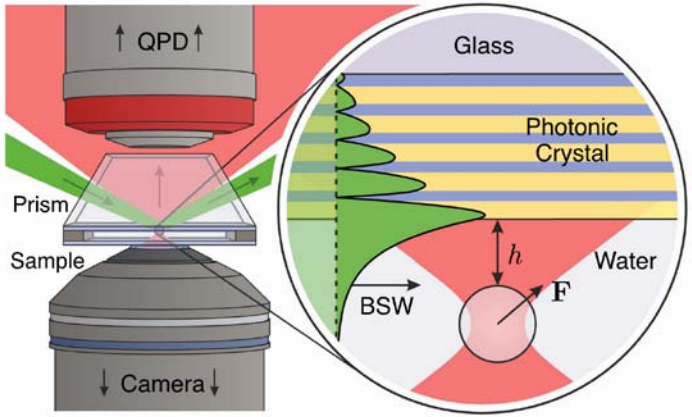


D. Shilkin et al. Opt. Lett. **40,** 4883 (2015)

- BSW visualization via enhanced fluorescence

- Giant Goos-Hanchen Effect

- Direct measurements of forces induced by BSW



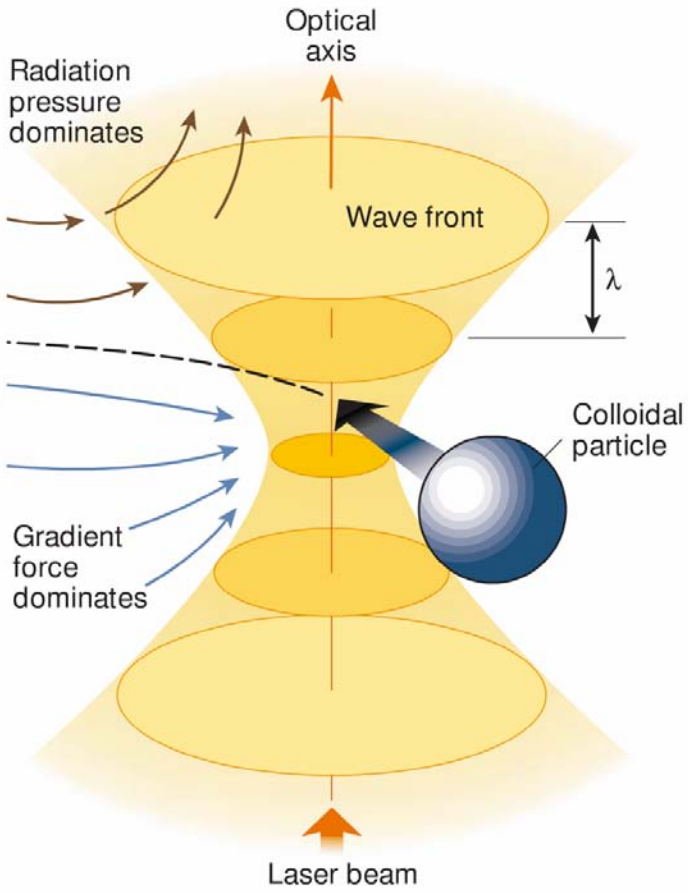
Optical Forces

used for optical manipulation
are divided into the gradient
and the scattering components

$$F_{grad} \propto \nabla \mathbf{E}^2$$

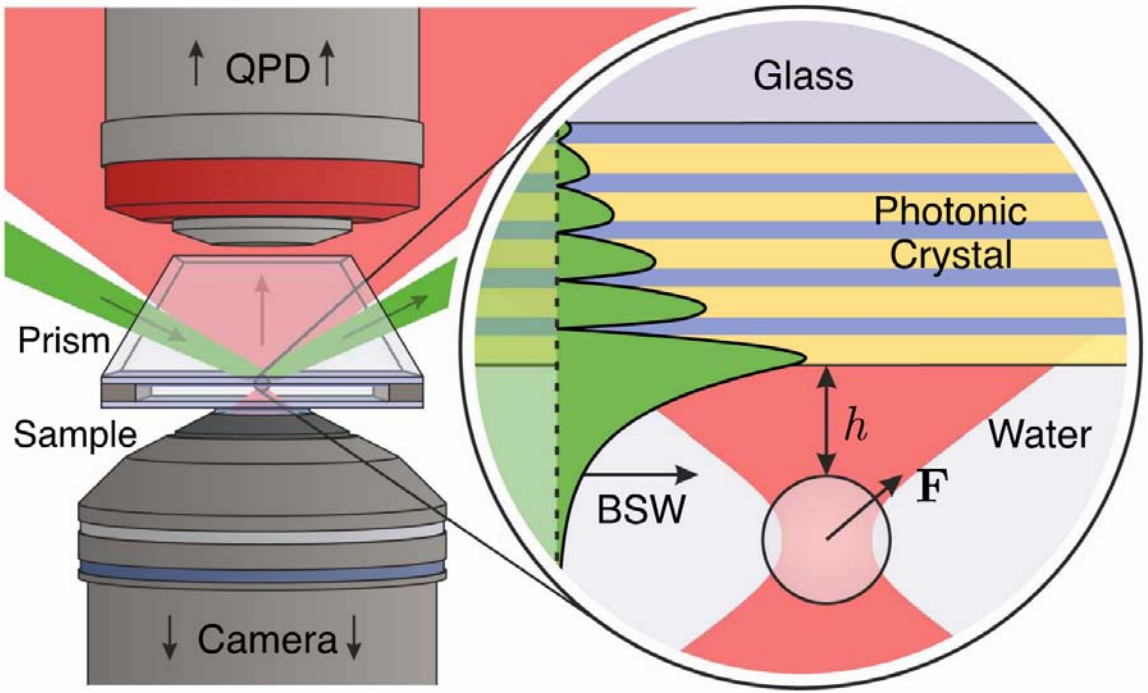
$$F_{scat} \propto \mathbf{E}^2$$

Optical tweezers:
trapping particles
with a tightly focused
laser beam



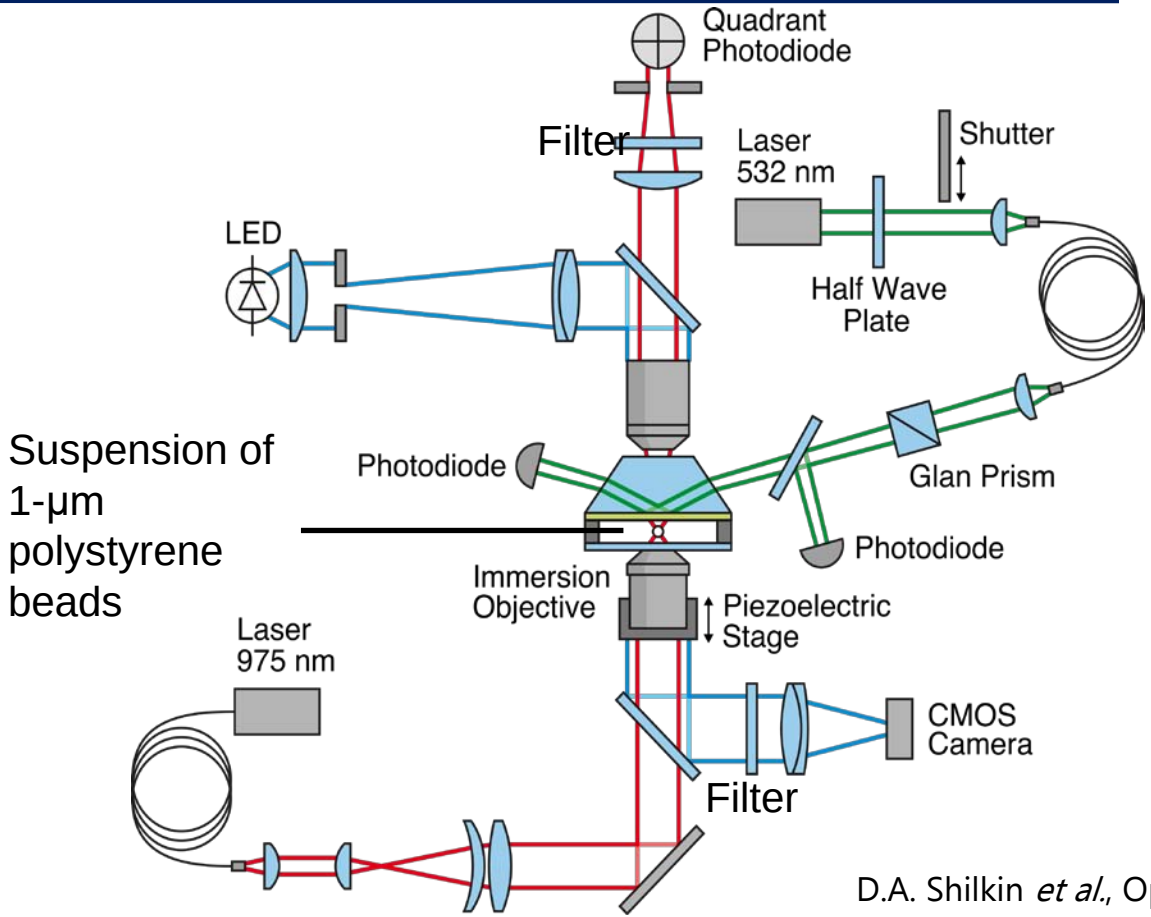
D.G. Grier, Nature **424**, 810 (2003)

Experimental Setup: the Idea



D.A. Shilkin *et al.*, Opt. Lett. **40**, 21 (2015)

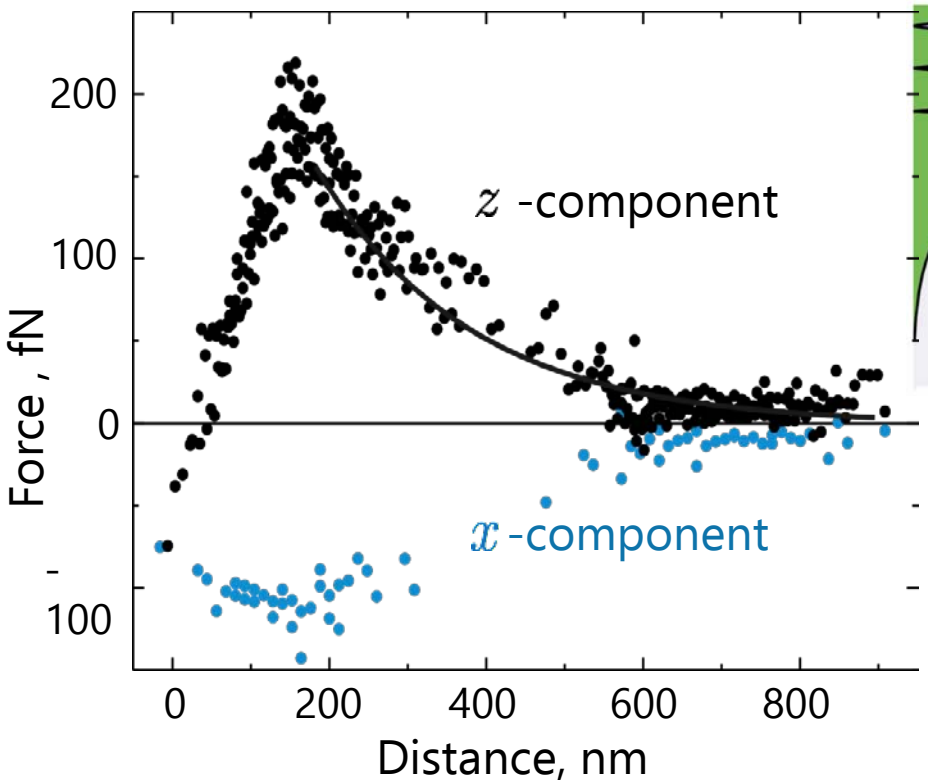
Experimental Setup: Realization

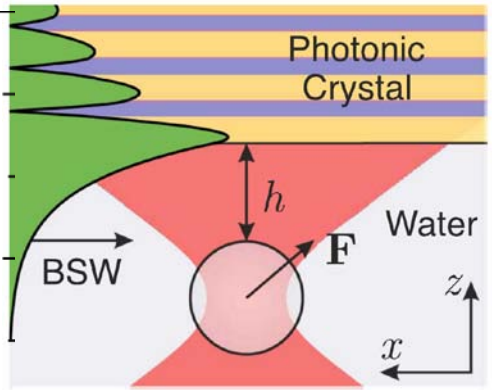


D.A. Shilkin *et al.*, Opt. Lett. **40**, 21 (2015)

Photonic Force Microscopy with BSW

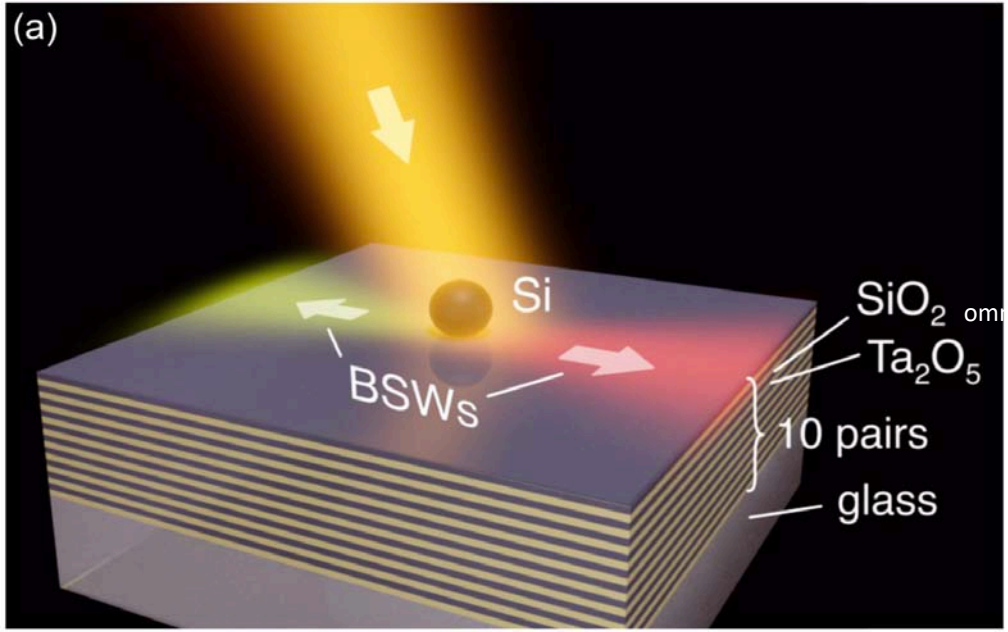
exponential decay at large distances and a surprising decrease at small ones



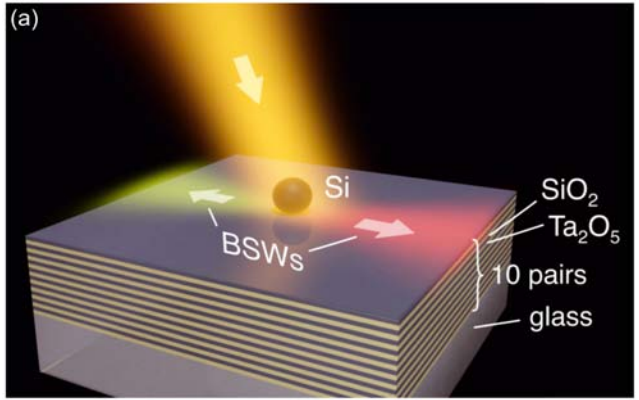


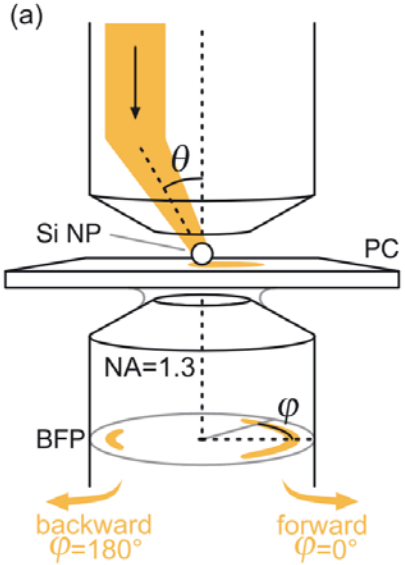
D.A. Shilkin *et al.*,
Opt. Lett. **40**, 21 (2015)

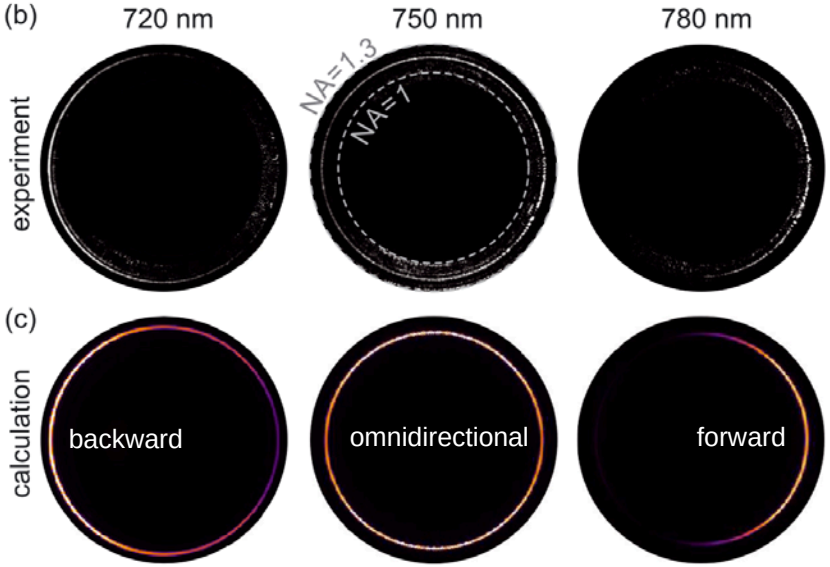
Mie-driven directional nanocoupler for BSW photonic platform

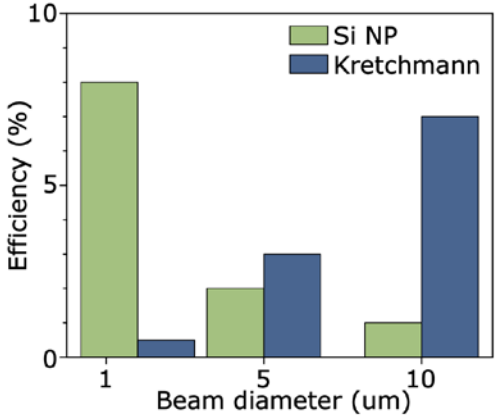


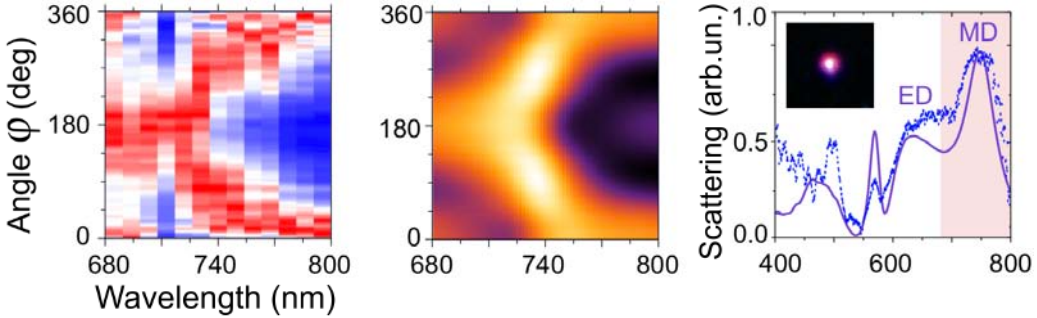
Mie-driven directional nanocoupler for BSW photonic platform







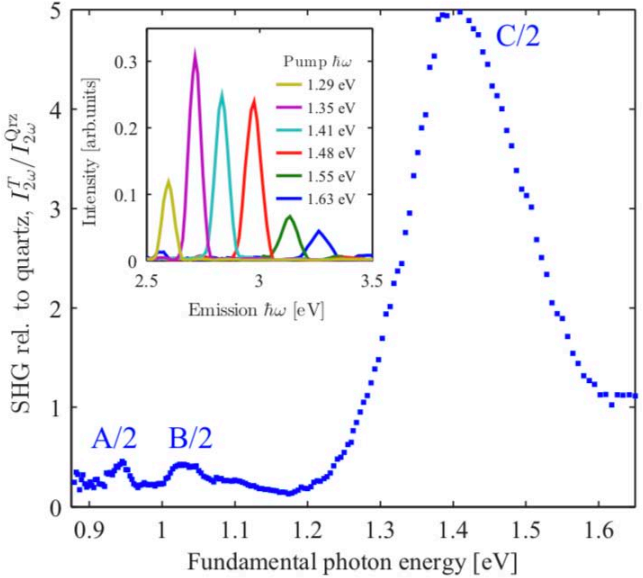




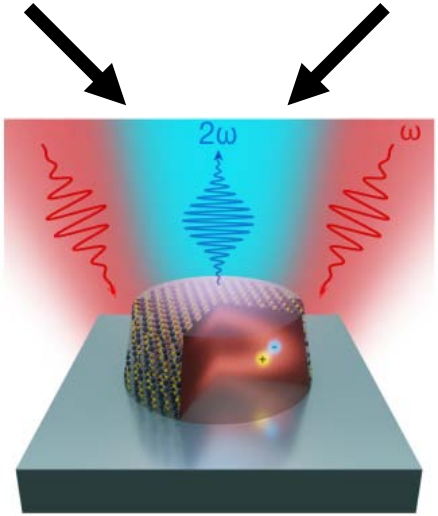
Nanophotonics 10, 2939 (2021)

Mie-resonant dielectric photonics with 2D semiconductors

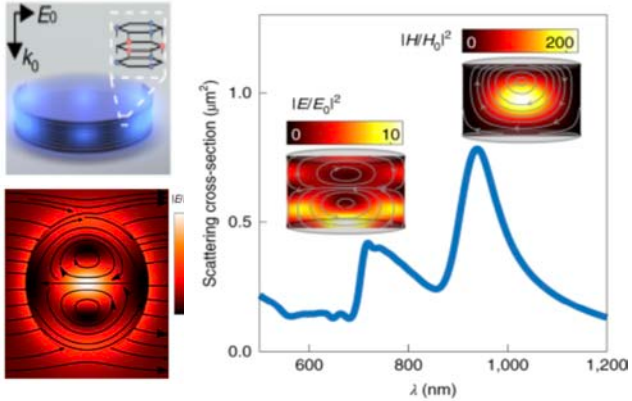
The nonlinear response of MoS_2 is enhanced near exciton wavelength



Trolle M.L. et al. *PRB* **92**, 161409 (2015)



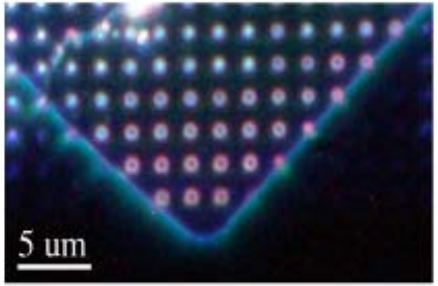
High refractive index of MoS_2 allow one to create the resonant structures



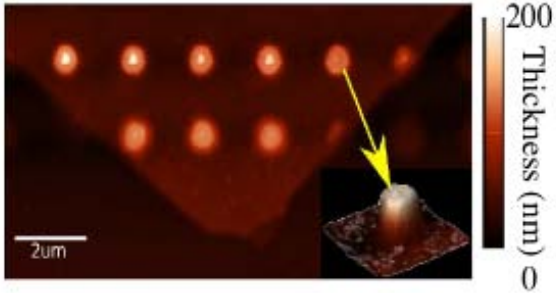
Verre R., et al. *Nature Nanotech* **14**, 679 (2019)

SHG enhancement by MD Mie-resonances at <u>fundamental</u> wavelength and exciton excitation on <u>SHG</u> wavelength

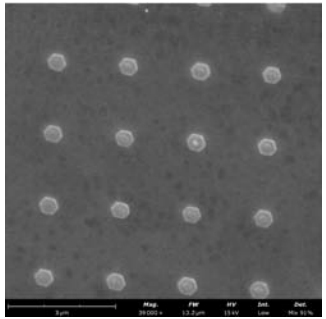
Mie-resonant dielectric photonics with MoS_2 nanodisks



Dark-field image

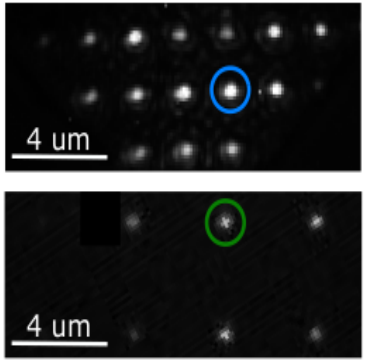


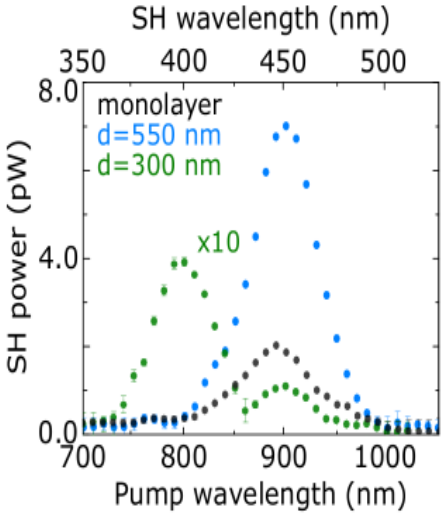
AFM

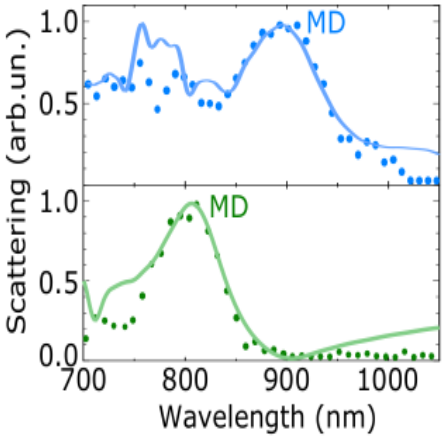


SEM

- 110 nm-thick exfoliated flake
- electron beam lithography
- reactive ion etching



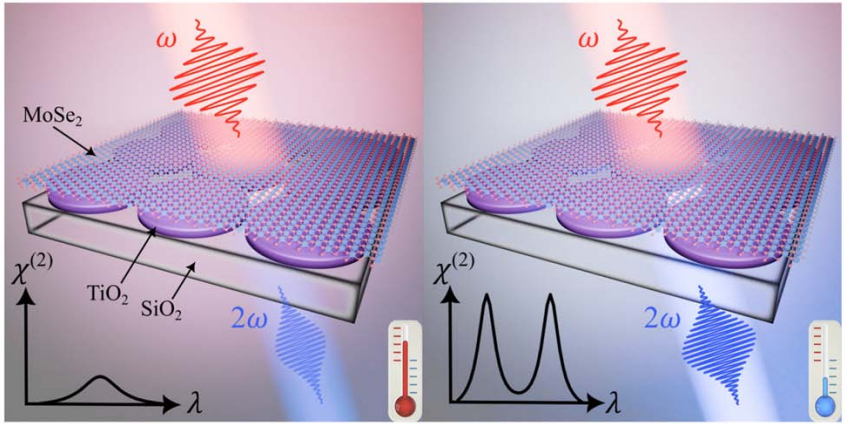


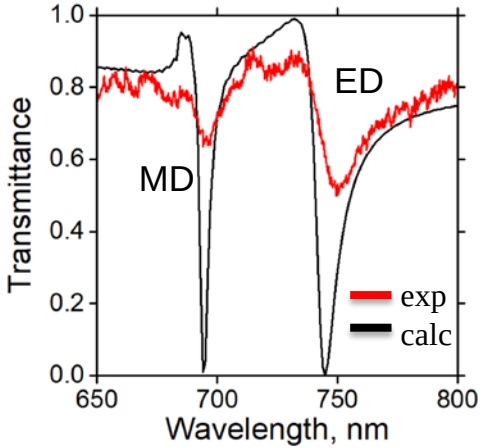


In the spectral region of the MD resonance, an increase in the SHG is observed

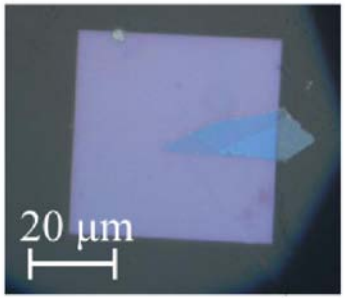
Laser Photonics Rev. **16**, 2100604 (2022)

Cryogenic SHG enhancement of TMDC monolayer coupled with high-Q dielectric metasurface





Spectral overlapping of high-Q resonance with exciton

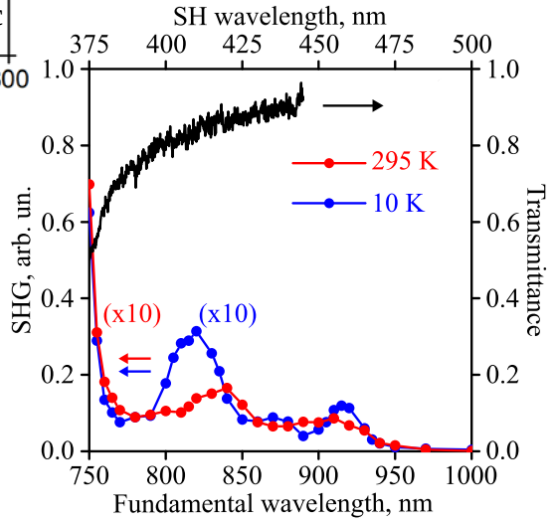


TiO_2

- dielectric
- low losses
- high refractive index (2.4)

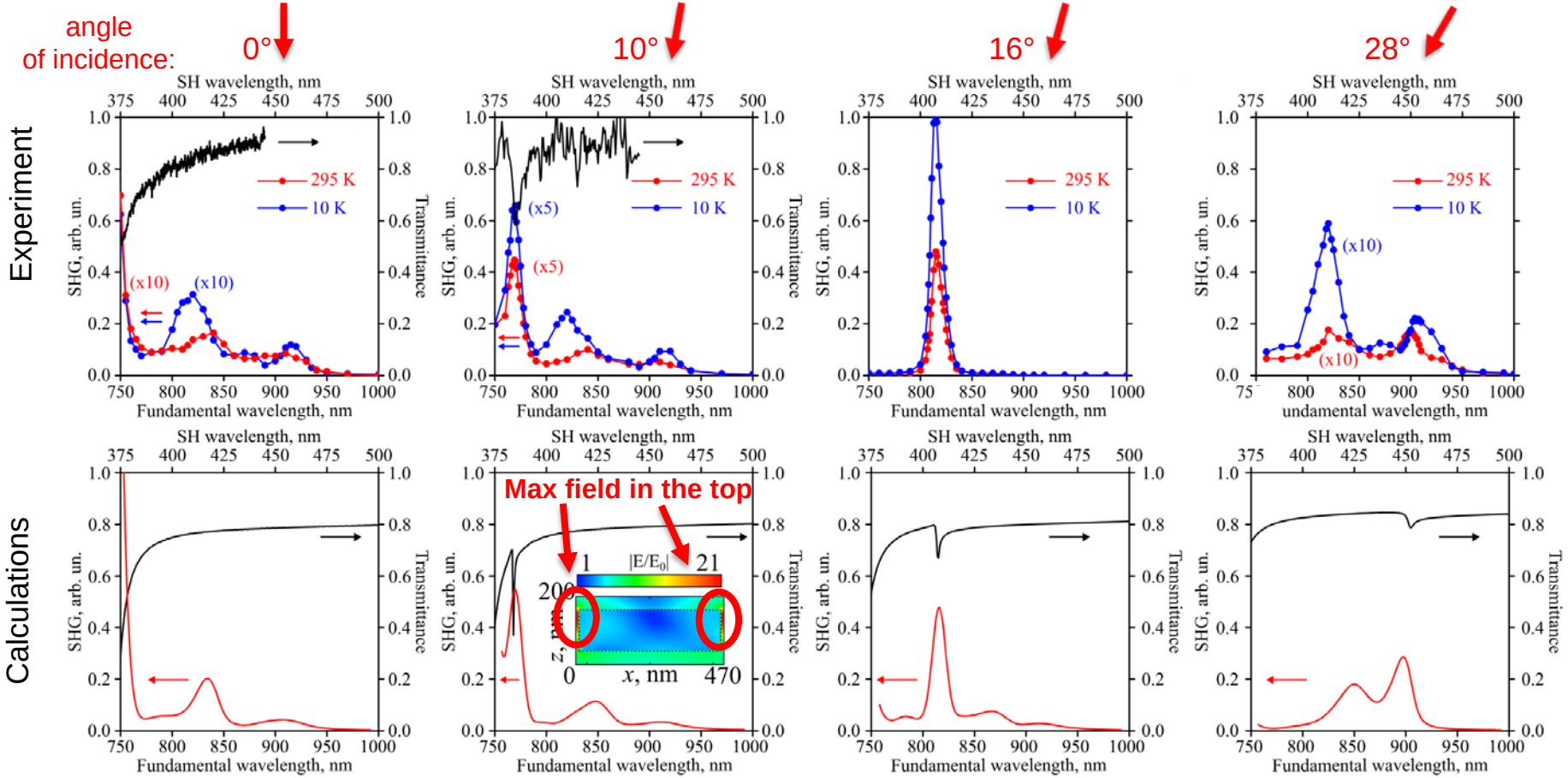
$MoSe_2$

- exciton ~800 nm (1.5 eV)
- high $\chi^{(2)}$ values



Nanophotonics **13**, 3429 (2024)

Nonlinear spectroscopy of high-Q dielectric metasurface



Nanophotonics **13**, 3429 (2024)

Фотоника и аналоговые вычисления

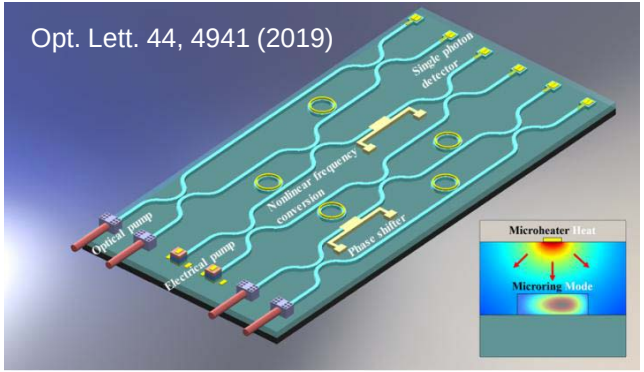
Преимущества фотоники

- Высокая тактовая частота
- Энергоэффективность
- Широкая полоса пропускания
- Помехоустойчивость

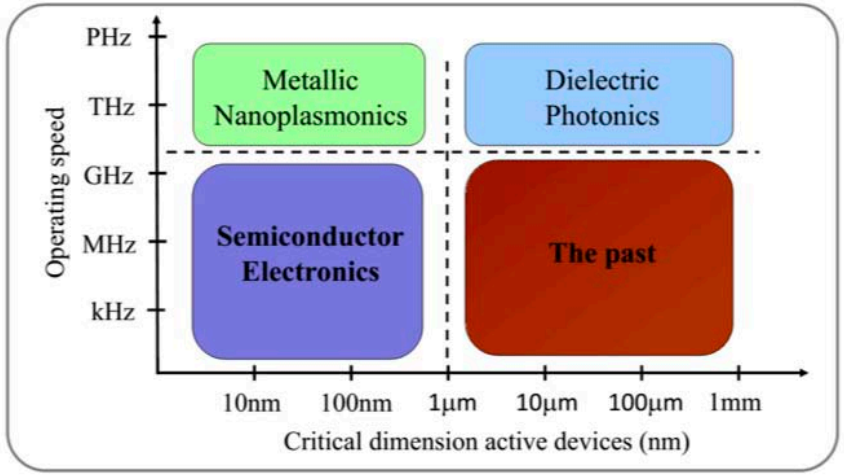
Недостатки

- Размер элементов ограничен длиной волны
- Проблемы оптического хранения информации

Интегральные фотонный чип



- *Возможность миниатюризации элементов*
- *Усиление нелинейных эффектов за счет резонансов*
- *Сверхбыстрые эффекты*



Метаповерхности для задач аналоговых вычислений

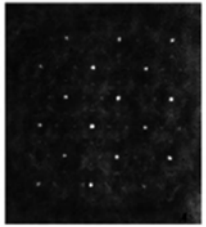
Устройства на основе метаповерхностей

- ахроматические металинзы
- генераторы голограмм
- фазовые корректоры
- пространственные модуляторы света

входное изображение

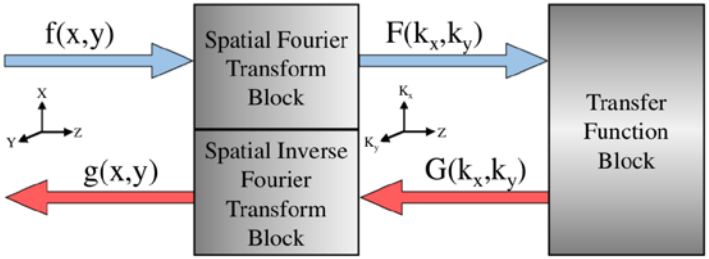
Фурье-фильтр буквы “O”

результат корреляции



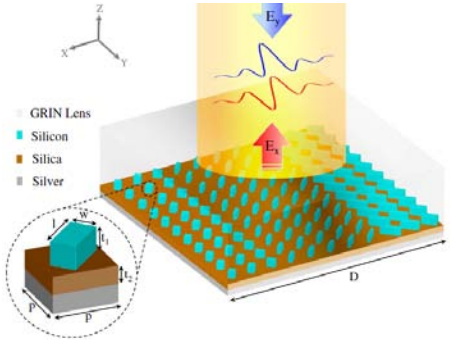
Применение метаповерхностей

- элементы сверточных нейронных сетей
- предобработка изображений
- выделение границ
- поиск опорных объектов на изображениях



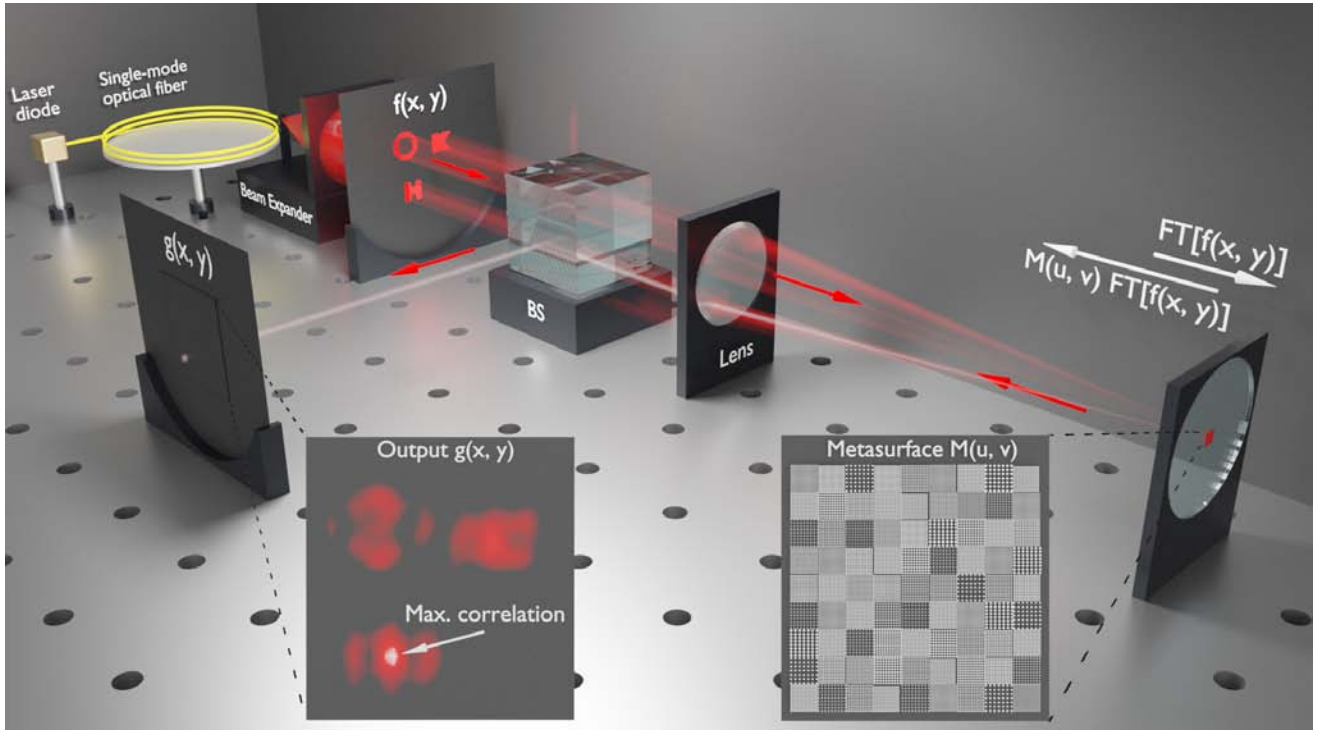
$$g(x,y) = h(x,y) * f(x,y) = \iint h(x-x', y-y') f(x',y') dx' dy'$$

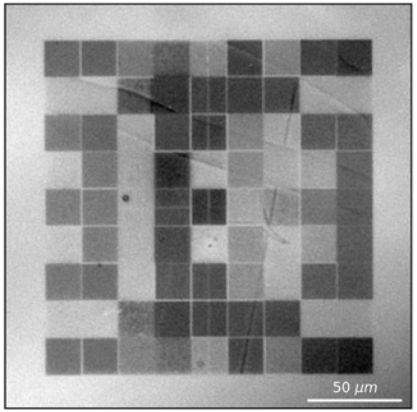
$$G(k_x, k_y) = H(k_x, k_y) F(k_x, k_y)$$



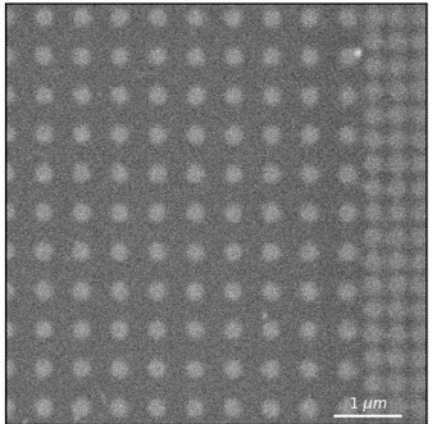
УФН **193**, 1284 (2023)

Fourier filtering system with a silicon metasurface





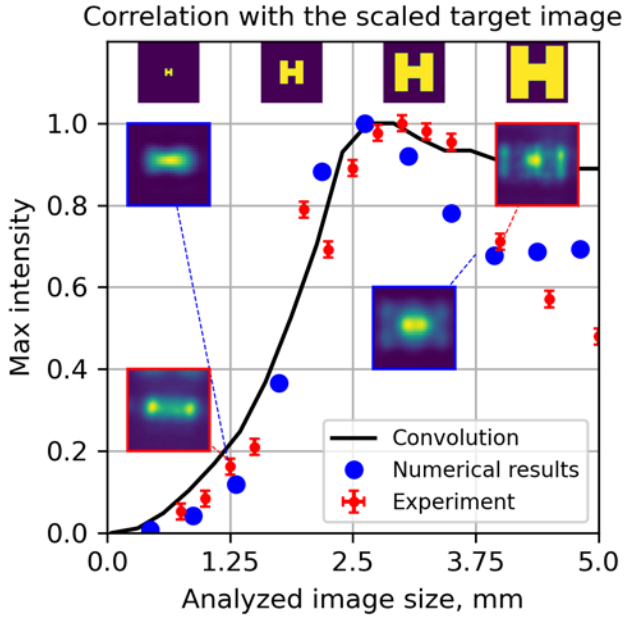
Bright-field microscope image of the whole metasurface

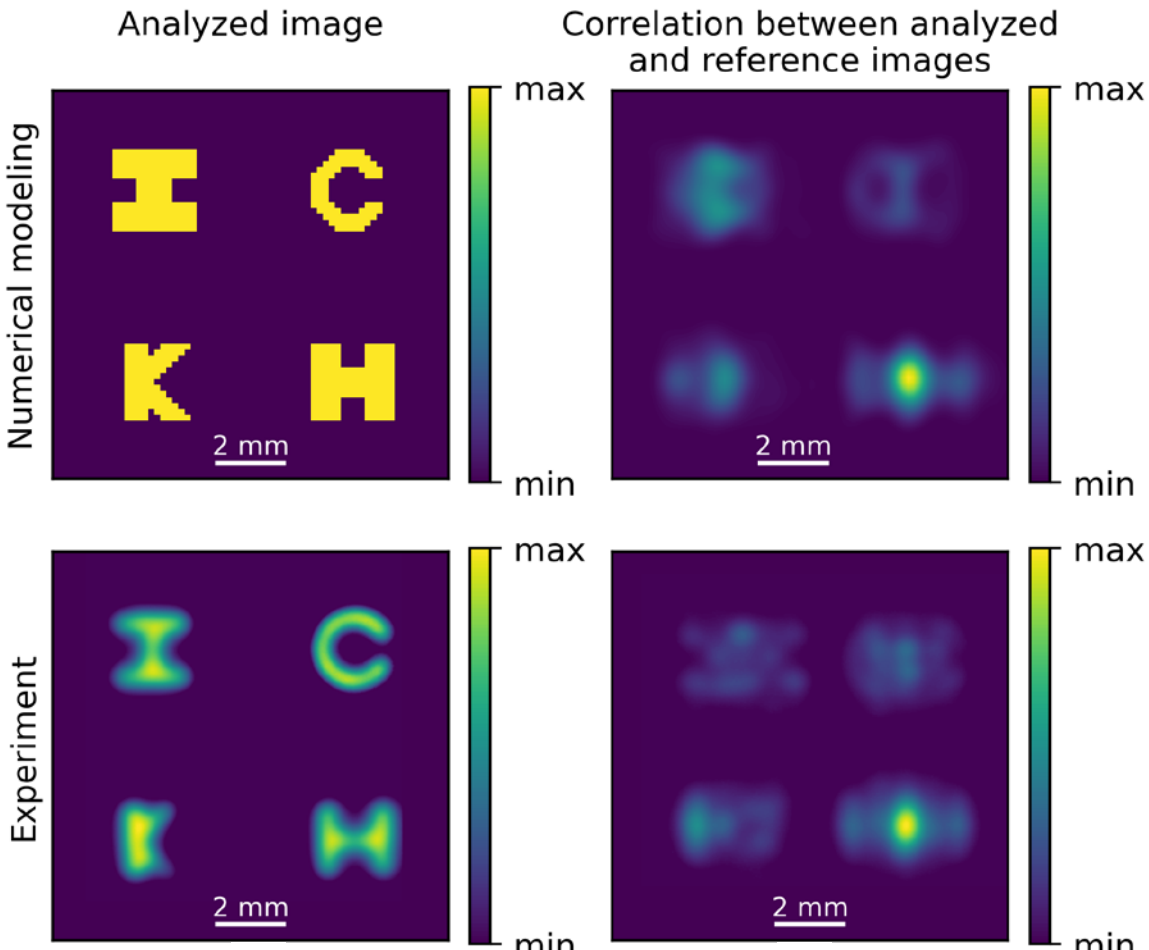


A SEM image of a region of the metasurface

ACS Photonics **11**, 2506 (2024)

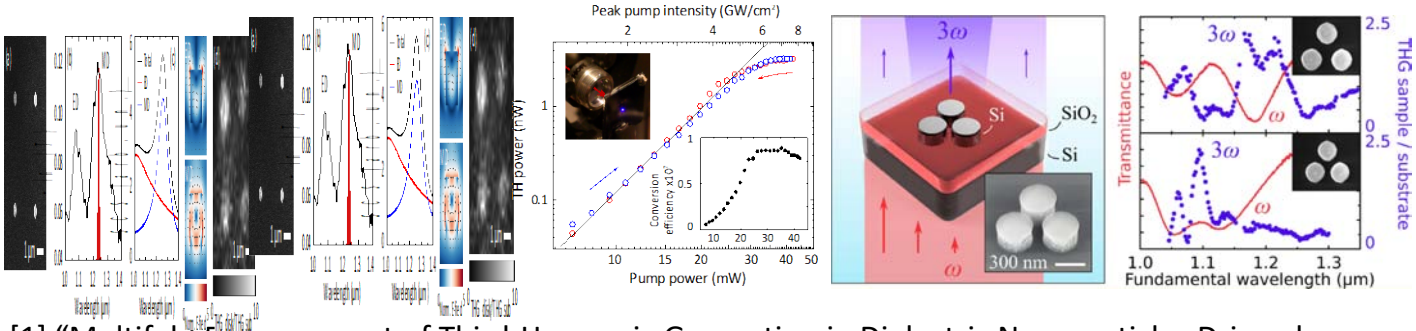
Fourier filtering system with a silicon metasurface





(top) Filtering of target images with different size.
(right) Filtering an image containing different letters in the presence of the target image.

ACS Photonics **11**, 2506 (2024)



[1] “Multifold Enhancement of Third-Harmonic Generation in Dielectric Nanoparticles Driven by Magnetic Fano Resonances,” *Nano Letters* **16**, 4857 (2016)

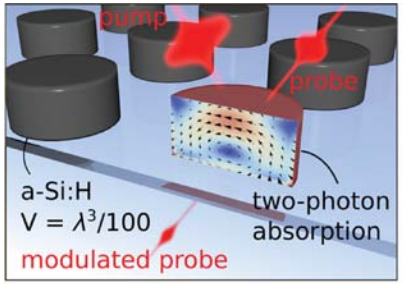
[2] “Ultrafast all-optical tuning of direct-gap semiconductor metasurfaces,” *Nature Communications* **8**, 17 (2017)

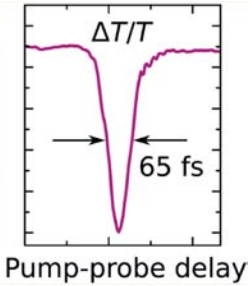
[3] “Enhanced nonlinear light generation in oligomers of silicon nanoparticles under vector beam illumination”, *Nano Letters* **20**, 3471 (2020)

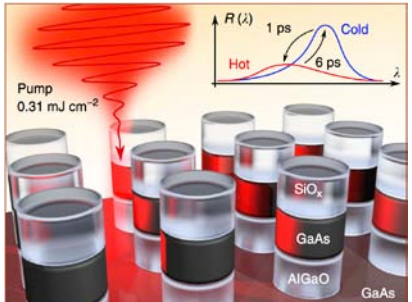
[4] “Analog optical correlation augmented by Mie-resonant metasurfaces”, *ACS Photonics* **11**, 2506 (2024)

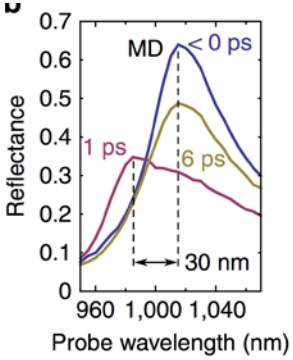
[5] “Cryogenic nonlinear microscopy of high-Q metasurfaces coupled with transition metal dichalcogenide monolayers ”, *Nanophotonics* **13**, 3429 (2024).

fedyanin@nanolab.phys.msu.ru









Acknowledgments

Boris Lukyanchuk, Alexander Shorokhov, Alexander Musorin, Varvara Zubyuk, Vladimir Bessonov and many others