How to Enhance Nonlinear Optical Signals at the Nanoscale

Presented by:

OSA Nonlinear Optics Technical Group

The OSA Nonlinear Optics Technical Group Welcomes You!

OSA Nonlinear Optics Technical Group

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DTU Fotonik, Denmark

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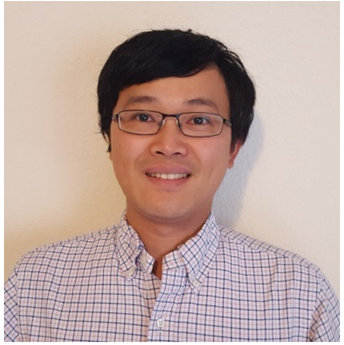

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Technical Group at a glance

- Focus
  - “Physics of nonlinear optical materials, processes, devices, & applications”
  - **3800** members (**largest** in OIS, 3rd largest in OSA)
- Mission
  - To benefit ***YOU***
  - webinars, e-Presence, publications, technical events, business events, outreach
  - Interested in presenting your research? Have ideas for TG events? Contact us at
- Email: TGNonlinearOptics@osa.org

  - Find us here
- www.osa.org/NonlinearOpticsTG
- Facebook: www.facebook.com/osanonlinearoptics
- LinkedIn: www.linkedin.com/groups/8302249

OSA Nonlinear Optics Technical Group

Today's webinar

Nonlinear Optics Technical Group

How to enhance non-linear optical signals at the nanoscale

Speaker's short Bio:
Graduation at Indian Institute of Technology in New Delhi, India
Ph.D. degree from ETH Zürich (CH)
Postdoc at the EPFL in Lausanne (CH)
Junior group leader at the Friedrich Schiller University, Jena (DE)

Prof. Dr. Rachel Grange

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ETH zürich

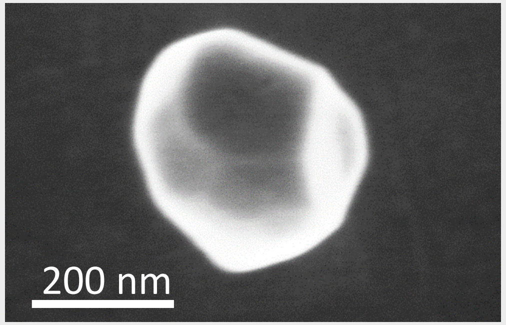
Department of Physics | Institute for Quantum Electronics

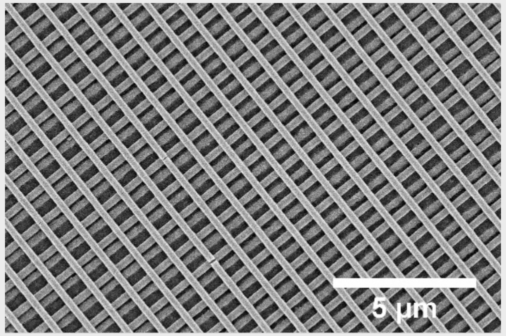
Optical Nanomaterial Group

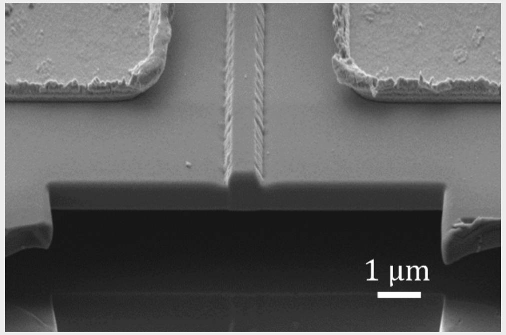
How to Enhance Nonlinear Optical Signals at the Nanoscale?

www.ong.ethz.ch

Beyond Metal and Semiconductors:
Nano-Oxides for Nonlinear Photonics Webinar







Rachel Grange
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How to Enhance Nonlinear Optical Signals at the Nanoscale?

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Andrea Morandi
Kevin Stalder
Damian Bucher
Iek Tang
Grégoire Saerens

Alumni: Anton Sergeyev, Nick Hendricks, Andrea Steinbrück, Eugenie Kim, Claude Renaut

Funding

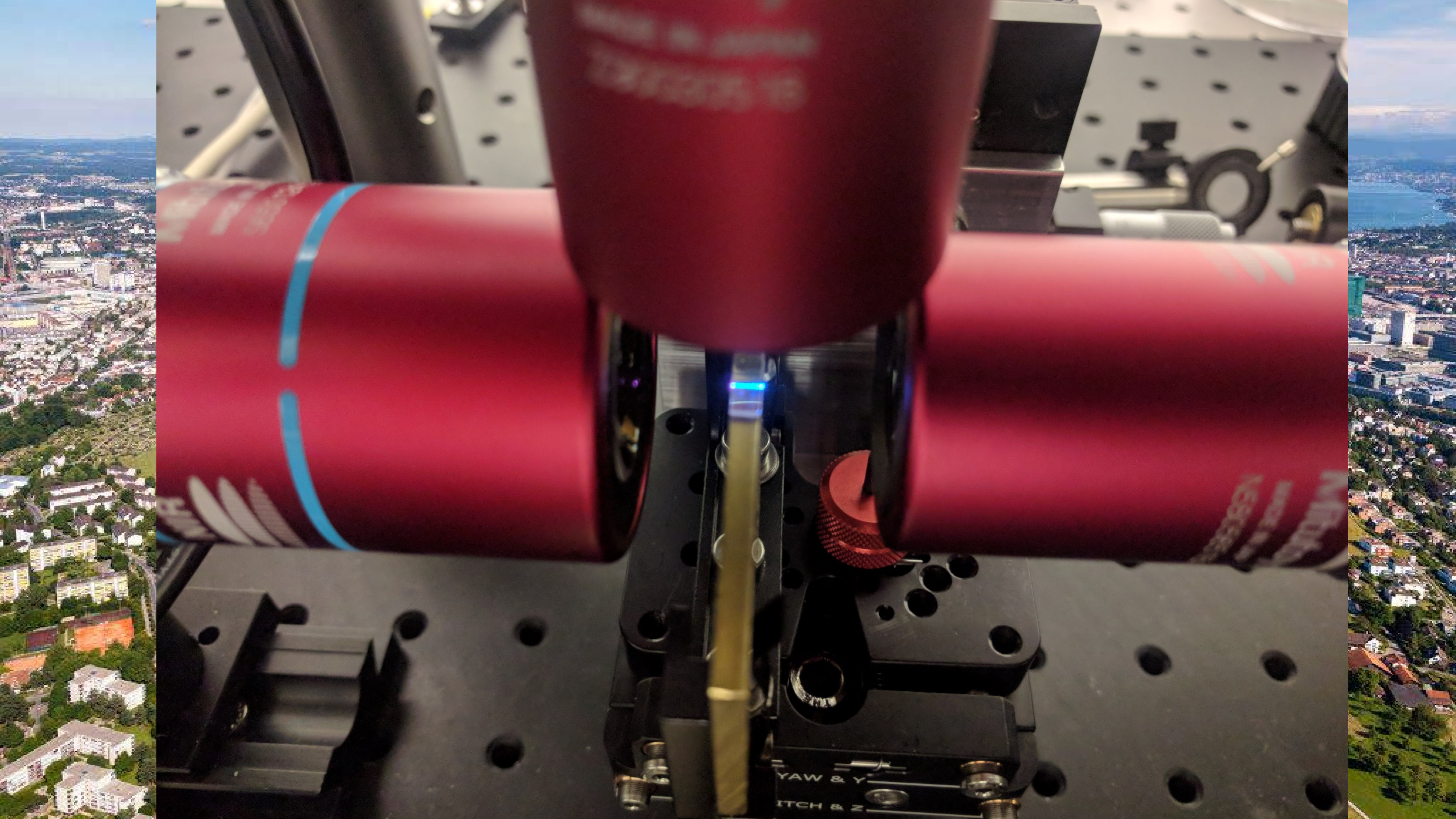
FNSNF
Fonds National Suisse
Schweizerischer Nationalfonds
Fondo Nazionale Svizzero
Swiss National Science Foundation

State Secretariat for Education, Research and Innovation SERI
Swiss Space Office

BRIDGE

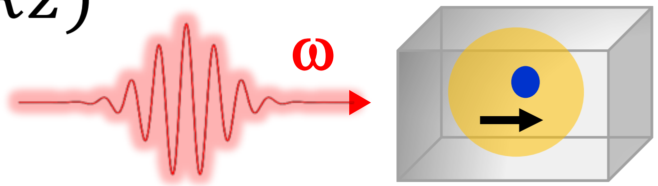
MARIE CURIE ACTIONS

erc
European Research Council
Established by the European Commission


YAW & Y

What is nonlinear optics ?

$$\vec{E}(t) = A\cos(\omega t + kz)$$



Induced dipole moment

No change under light

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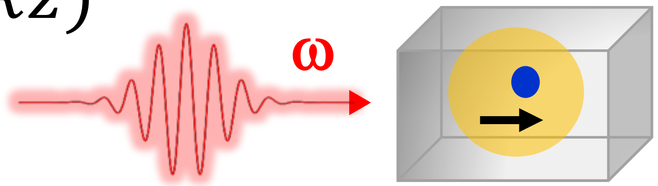


No change under light

Induced dipole moment

Linear regime

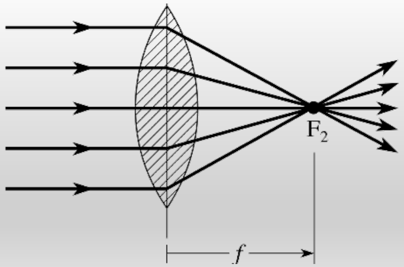
Induced Polarization

$$\vec{P} = \varepsilon_0 \chi^{(1)} \vec{E}$$

dielectric constant of the vaccuum

$\chi^{(1)}$ Electric susceptibility

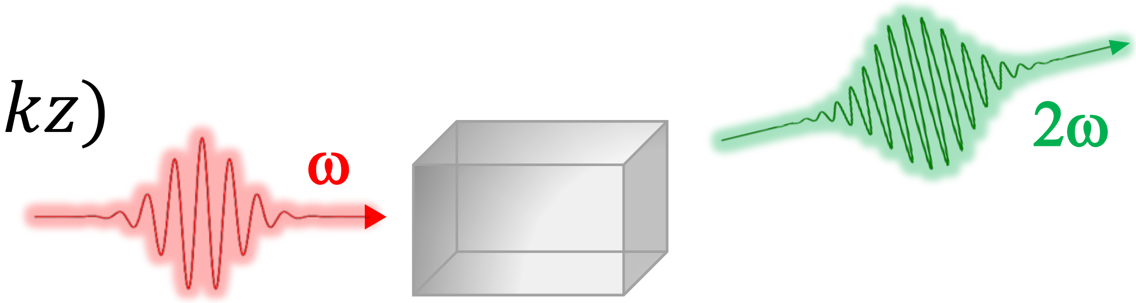
$$n^2 = 1 + \chi$$



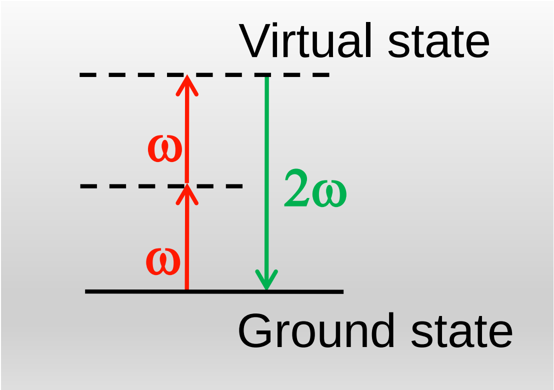
no longer valid for intense light

What is nonlinear optics ?

$$\vec{E}(t) = A\cos(\omega t + kz)$$



Second Harmonic Generation



Nonlinear regime

Induced Polarization

$$\vec{P} = \varepsilon_0 \chi^{(1)} \vec{E} + \varepsilon_0 \chi^{(2)} \vec{E}^2 + \varepsilon_0 \chi^{(3)} \vec{E}^3 + \cdots$$

Second order susceptibility

Second Harmonic Generation (SHG)

Franken et al., Phys Rev Lett, 7,4 1961

What is nonlinear optics ?

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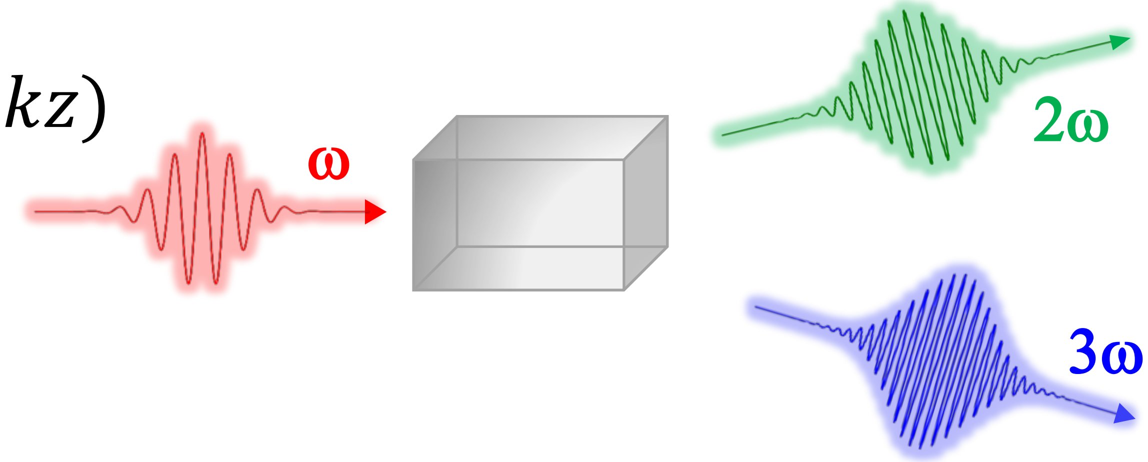

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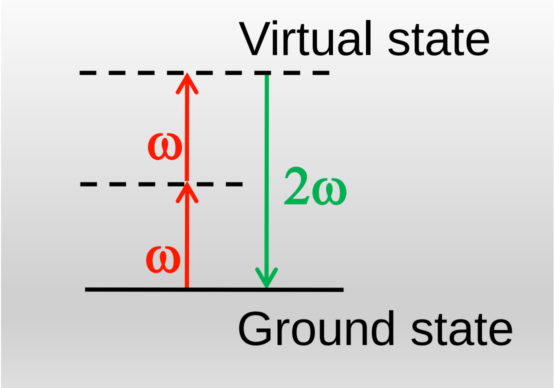

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$$\vec{P} = \varepsilon_0\chi^{(1)}\vec{E} + \varepsilon_0\chi^{(2)}\vec{E}^2 + \varepsilon_0\chi^{(3)}\vec{E}^3 + \cdots$$

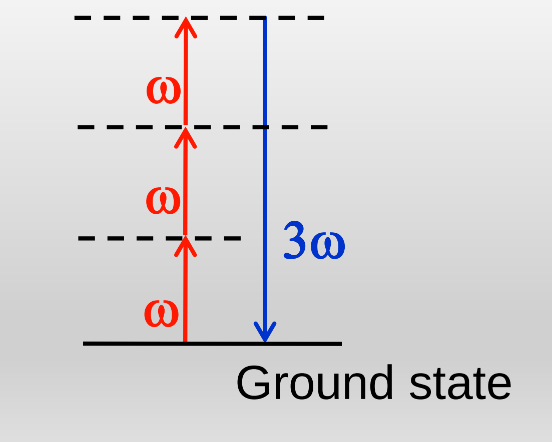
Second order susceptibility

Third order susceptibility

Second Harmonic Generation (SHG)

Third harmonic generation

Third harmonic generation



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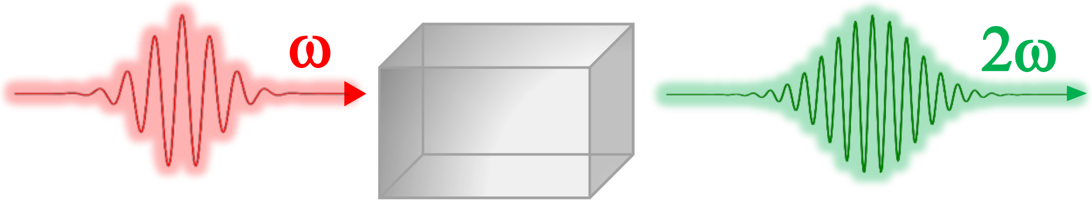
Why is nonlinear optics useful?

Green pointer



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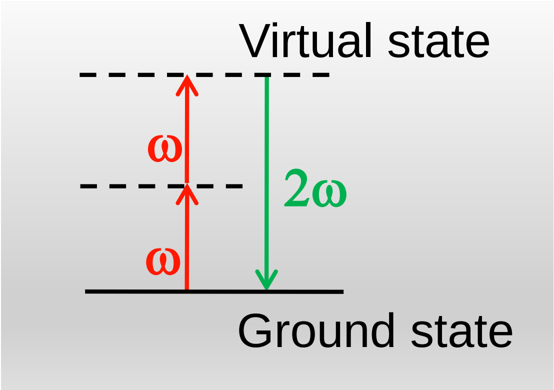
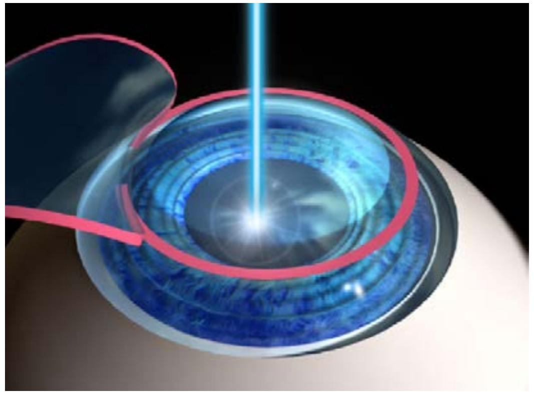
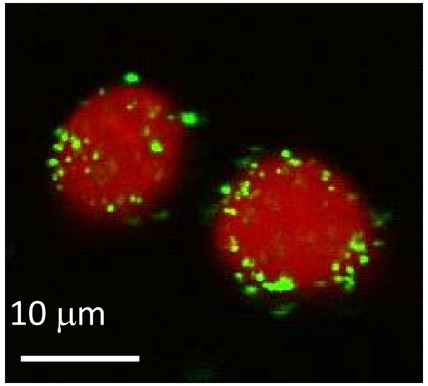


Laser for eye surgery



Bioimaging



Hsieh, Grange et al, Opt. Exp. 2009

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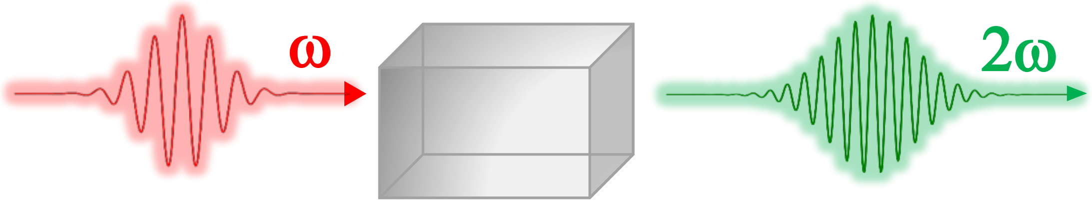

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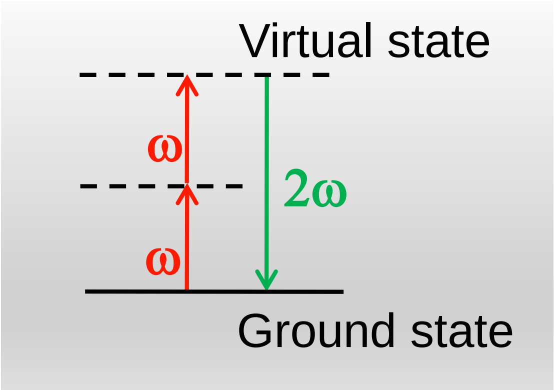

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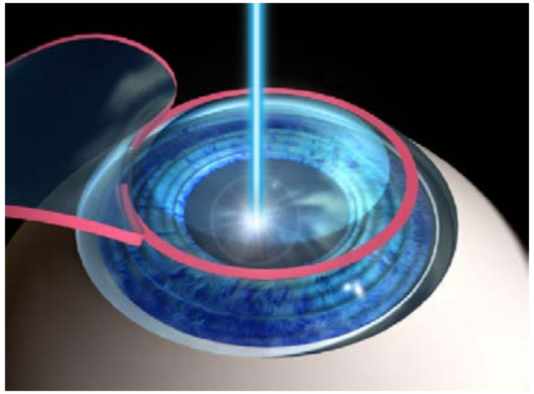

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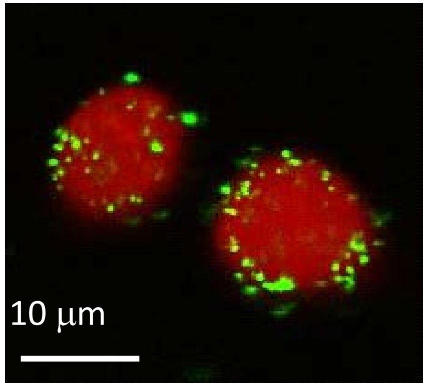

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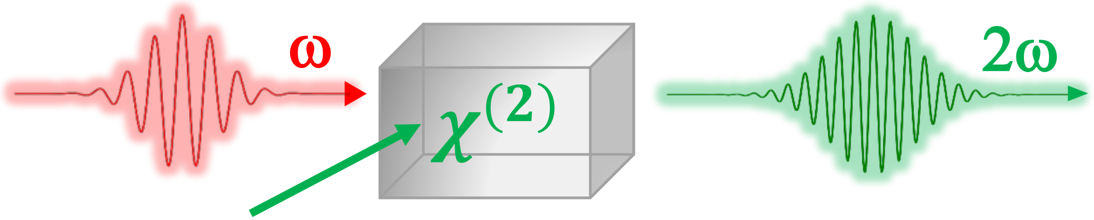
Advantages

- + Photon interactions
- + Generation of new color: UV to NIR
- + Spectral filtering (no bleaching)
- + Coherent signal
- + Ultrafast response
- + Revealing crystalline structure

Why is nonlinear optics useful?



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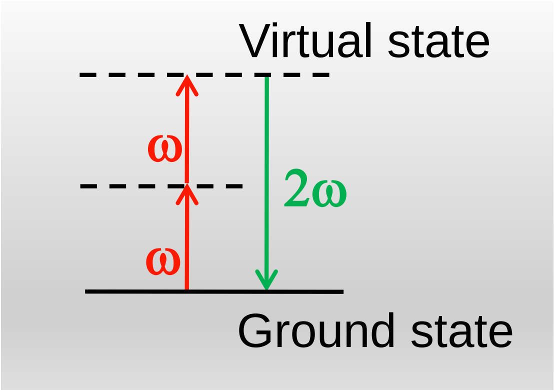

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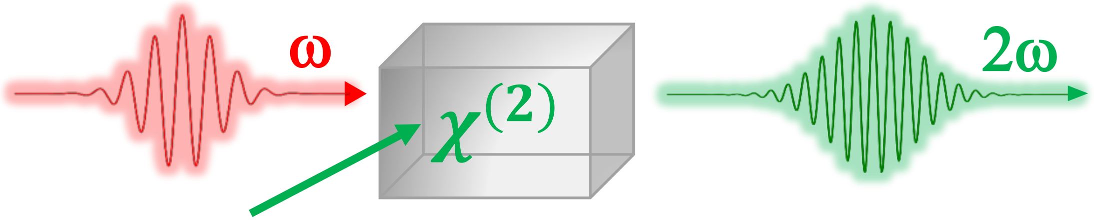

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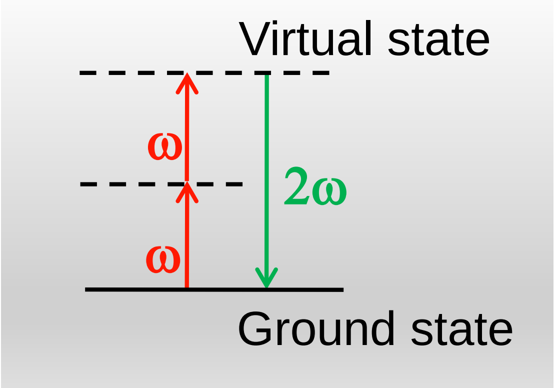
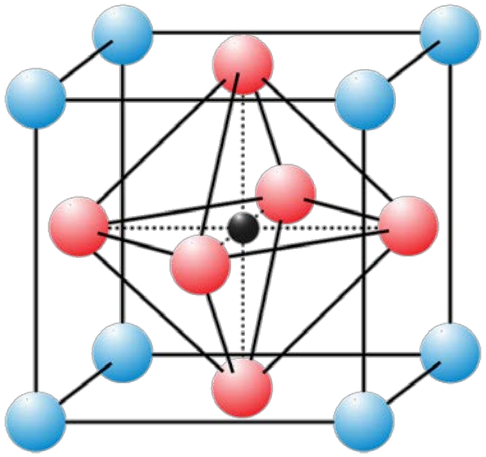


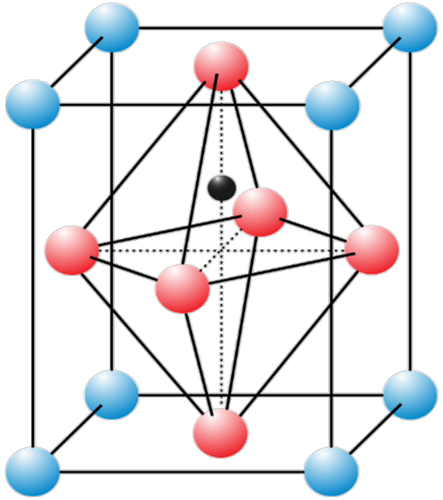
Centrosymmetric

$\chi^{(2)} = 0$



Non centrosymmetric

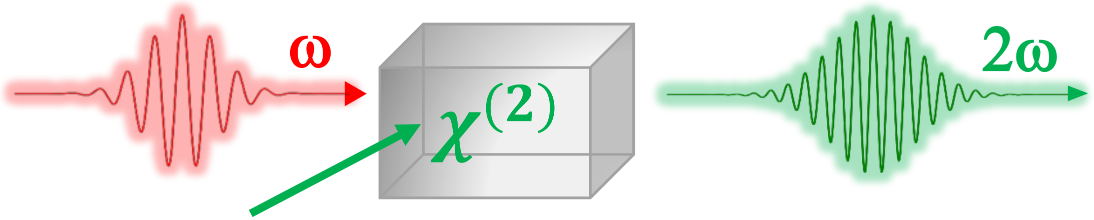
$\chi^{(2)} \neq 0$



Tensor coefficients

Material	$\chi^{(2)}$ coeff. (pm/V)
Silicon	0
SiO_2 (Quartz)	0.335
$BaTiO_3$	6.8 to 17
$LiNbO_3$	6 to 34
GaAs	134 to 256

Why is nonlinear optics useful?



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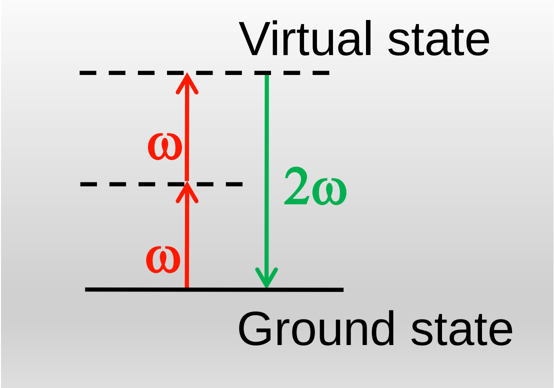

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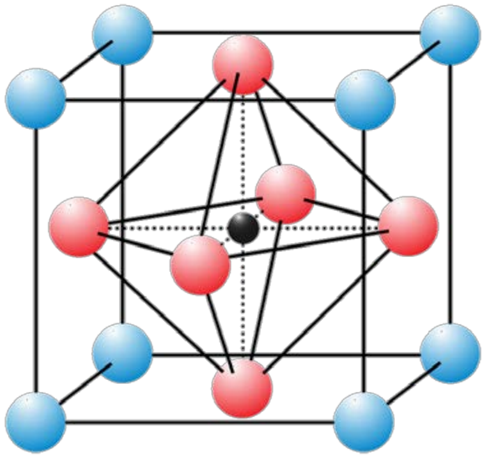

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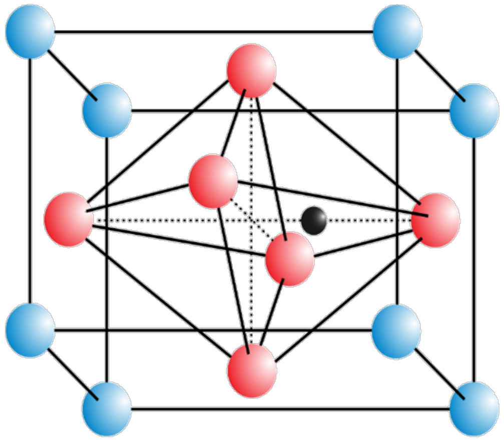

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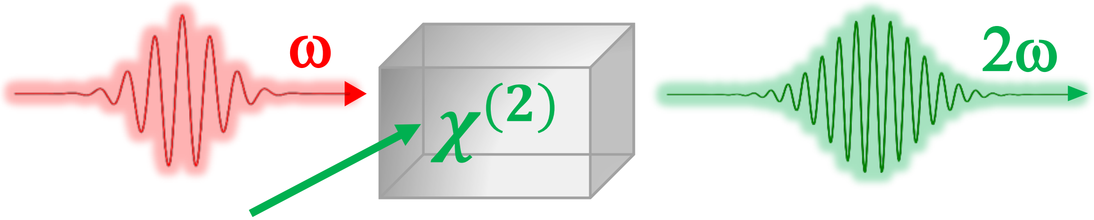

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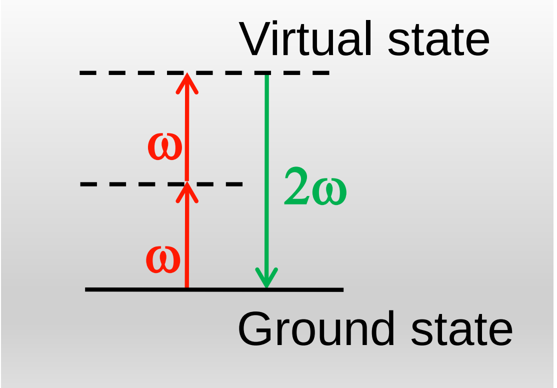

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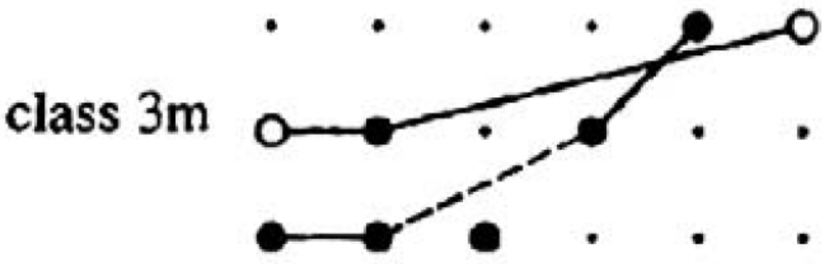

Lithium niobate

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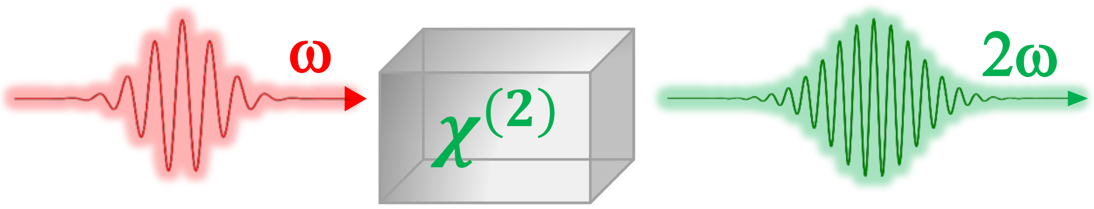
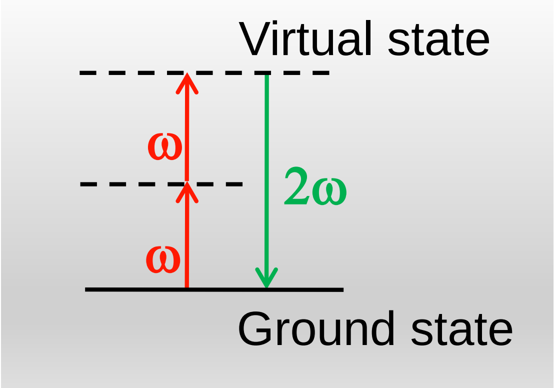
R. W. Boyd, Nonlinear Optics (Academic Press, 2008)

Why the metal-oxides ?



Second Harmonic Generation



Advantages of metal-oxides ($\chi^{(2)}$ materials)

- **Barium titanate, Lithium niobate as bulk**
- **High nonlinearities**
- **Large band gap: 3-4 eV**
- **Refractive index > 2**
- **Electro-optic, ferroelectric,...**

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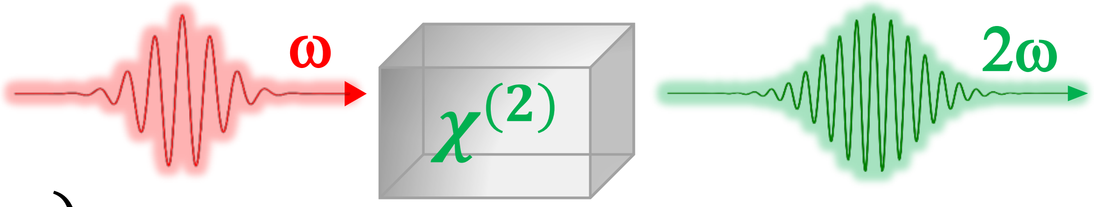
How is the interaction within the material ?

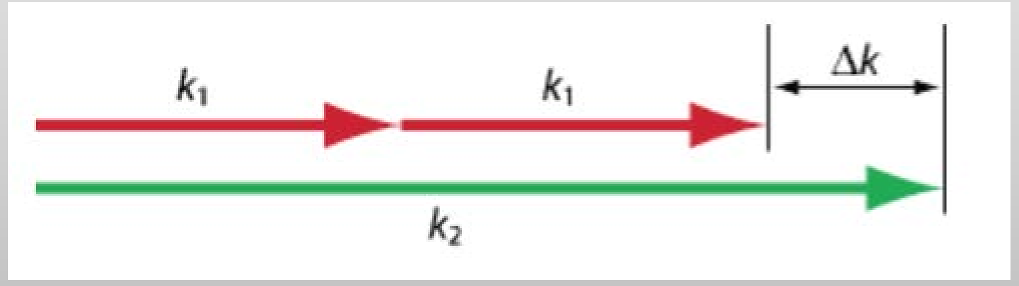


$$\vec{E}(t) = A cos(\omega t + kz)$$

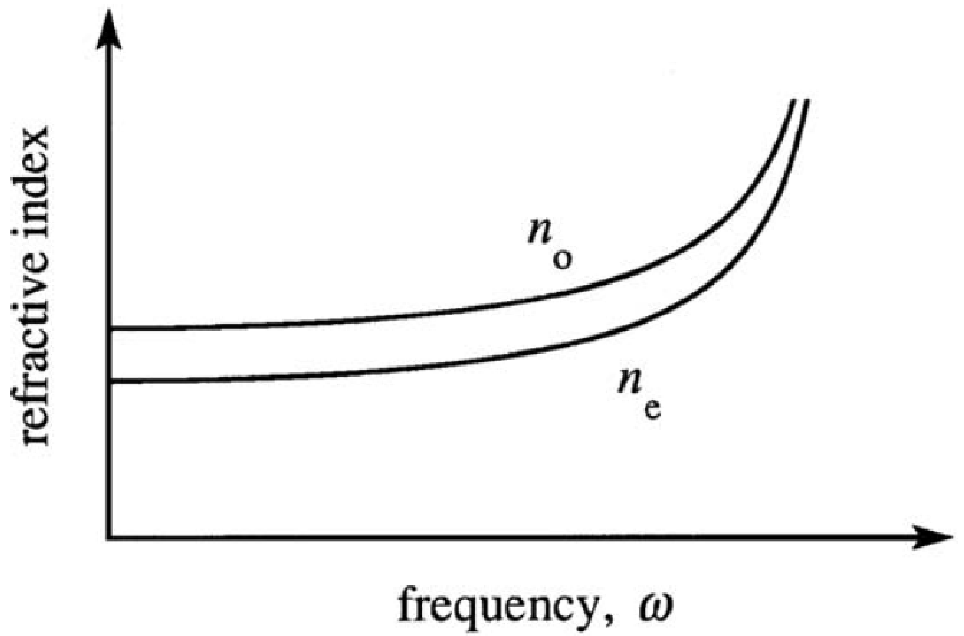
wavenumber

Phase mismatch due to dispersion

Phase mismatch $\Delta \boldsymbol{k} \neq \mathbf{0}$



Chromatic dispersion : *n(ω)≠ n(2ω)*



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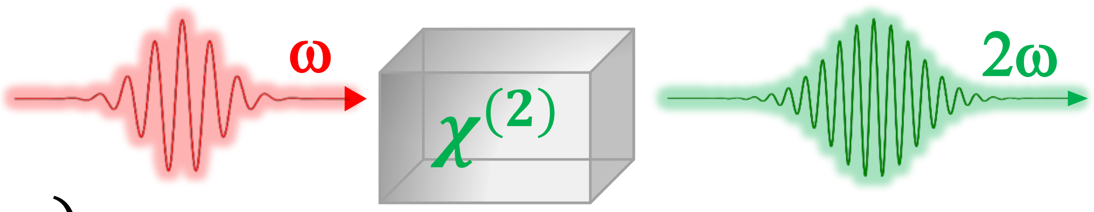

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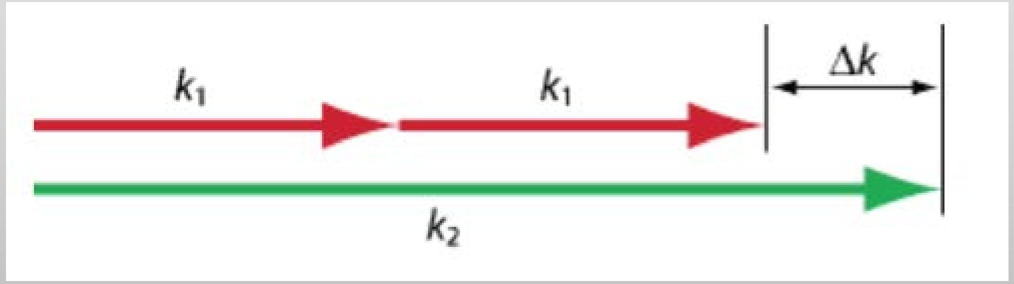

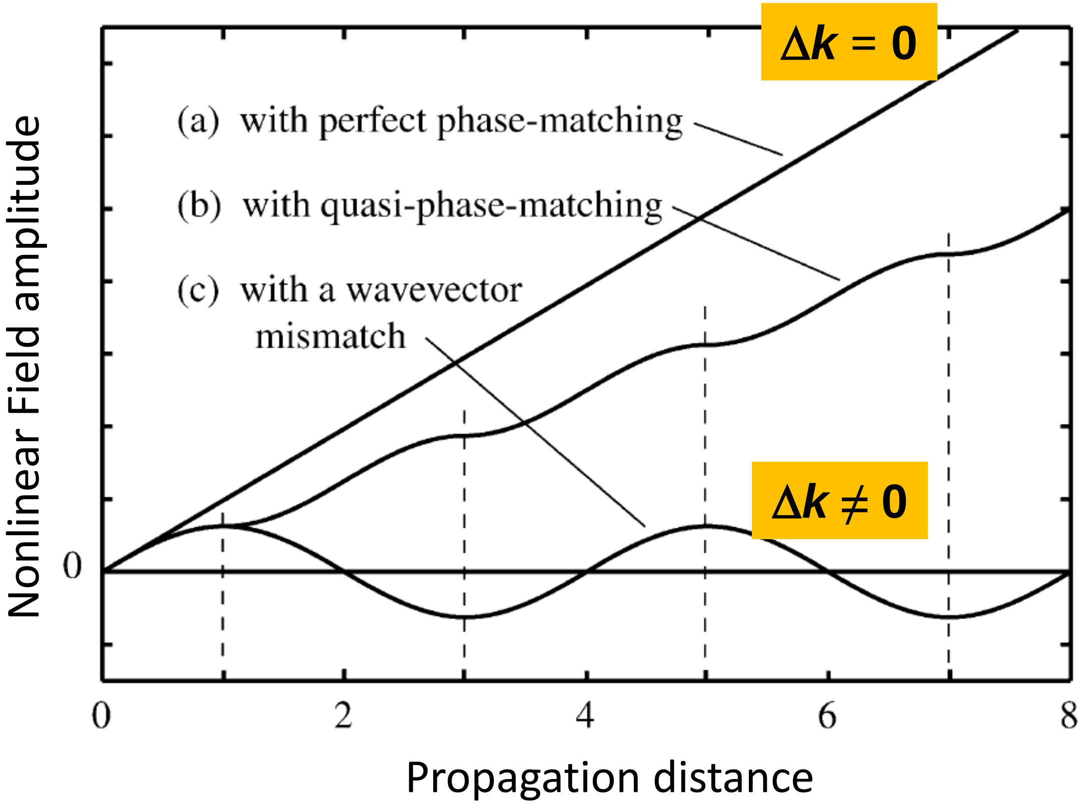

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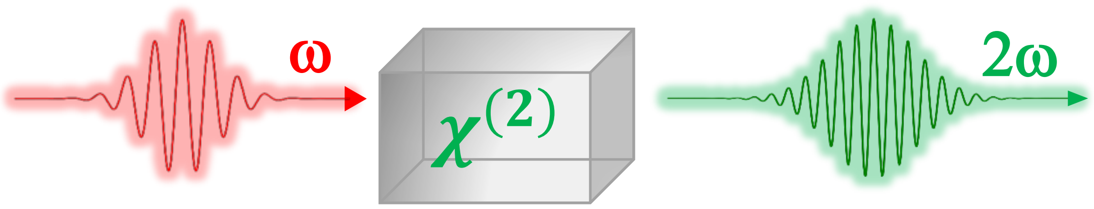
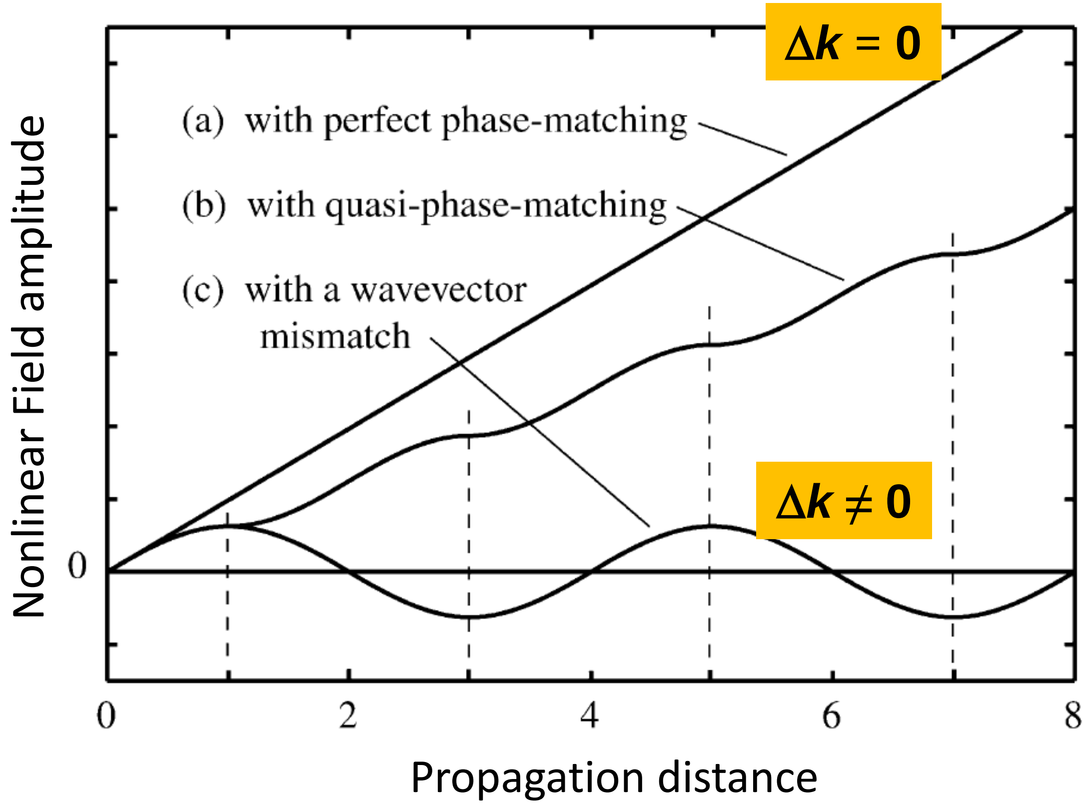
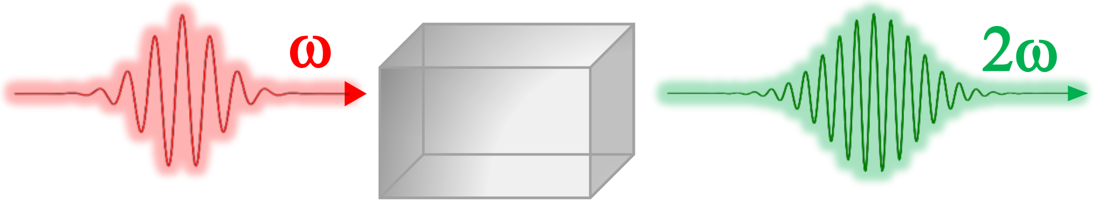


How to deal with phase matching ?

- Periodical poling
- Angle or temperature tuning
- In waveguides:
  modal phase-matching
- **Reducing the size of the material**



Limitations of current nonlinear optics



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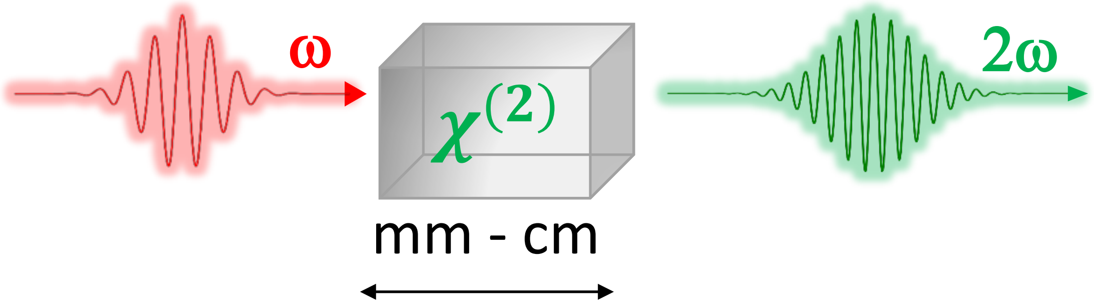
Limitations

- High power **-> high energy cost and damage**
- Bulky material **-> no integration**
- Phase mismatch **-> low output signal**
- Small sizes -> **reduced signal output**

My goal

Limitations of current nonlinear optics



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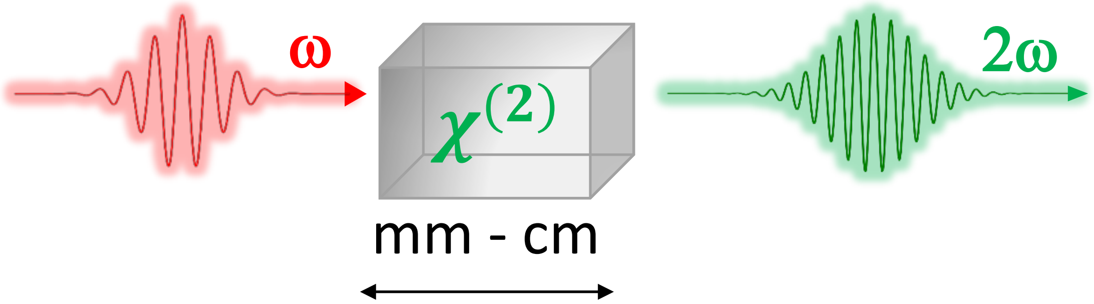

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My goal

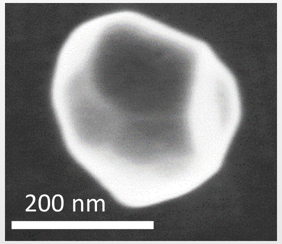
Resonance or confinement

in particles and thin films

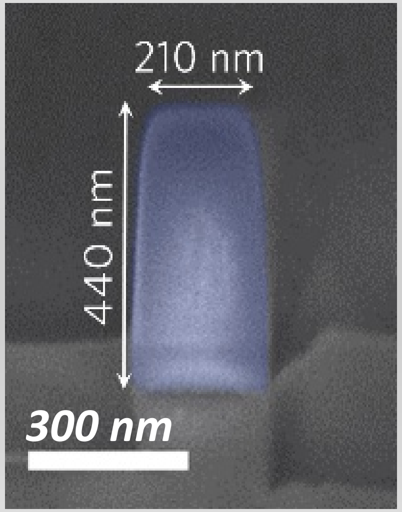
to achieve compact devices

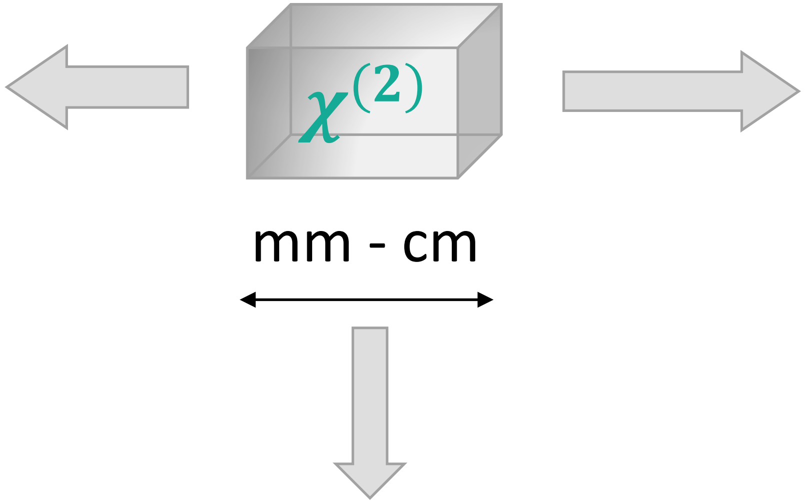
$\chi^{(2)}$ materials at small scale

$\chi^{(2)}$ Building blocks



20 - 100s nm





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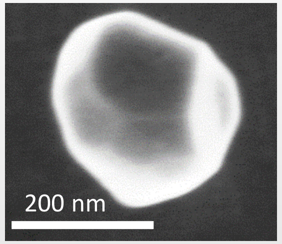

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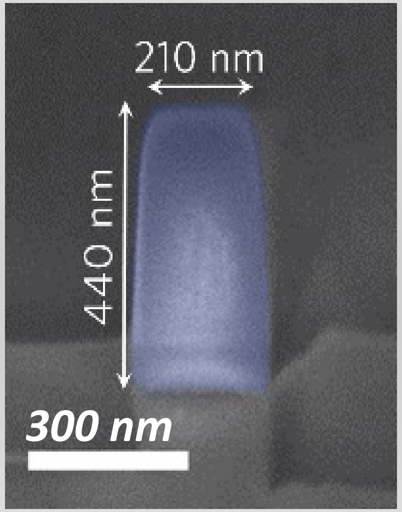
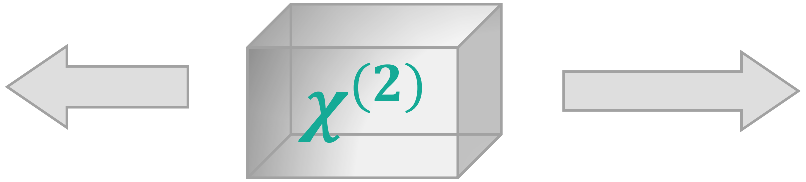
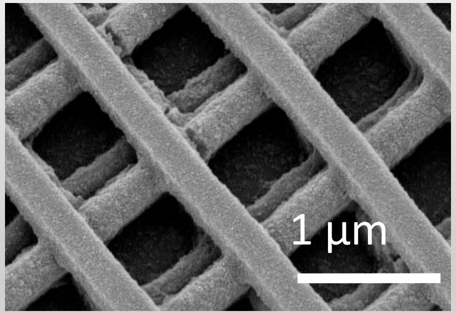




mm - cm

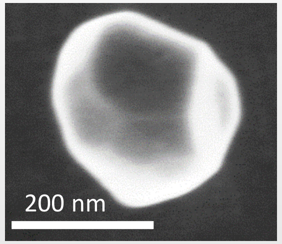
Bottom-up processing

Wide surface area photonic crystal

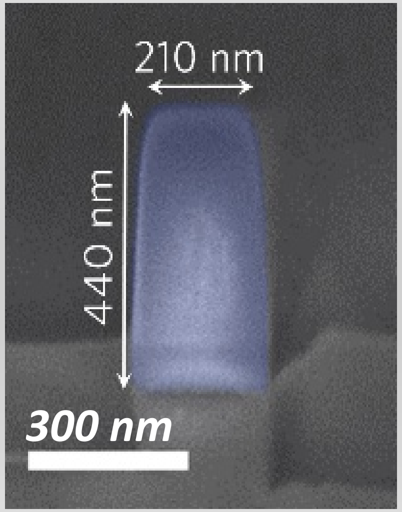


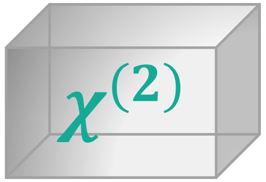
$\chi^{(2)}$ materials at small scale

$\chi^{(2)}$ Building blocks



20 - 100s nm

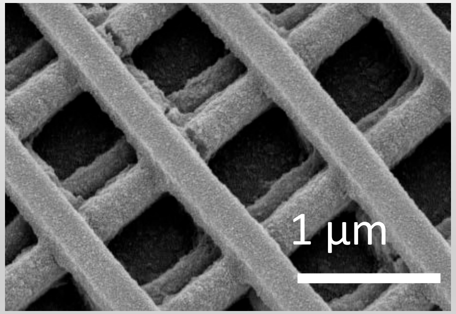




mm - cm

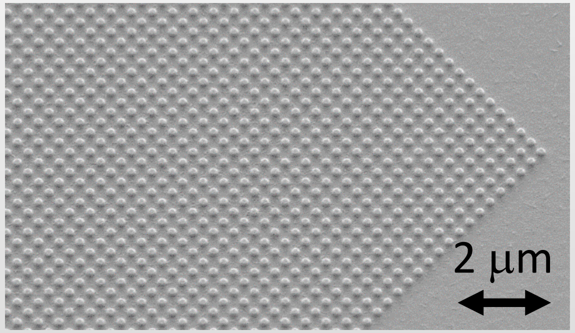
Bottom-up processing

Wide surface area photonic crystal

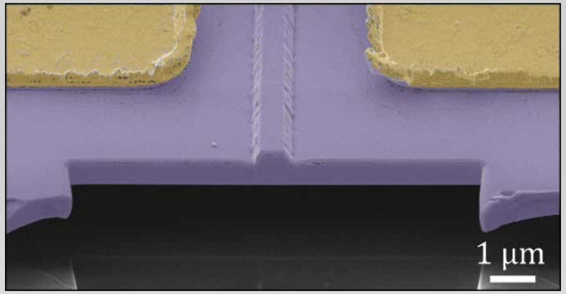


Top-down fabrication

Flat photonic structures

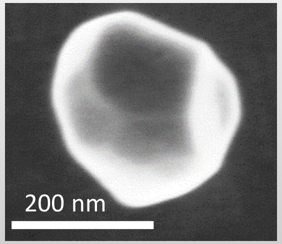


Integrated devices



A powerful characterization tool

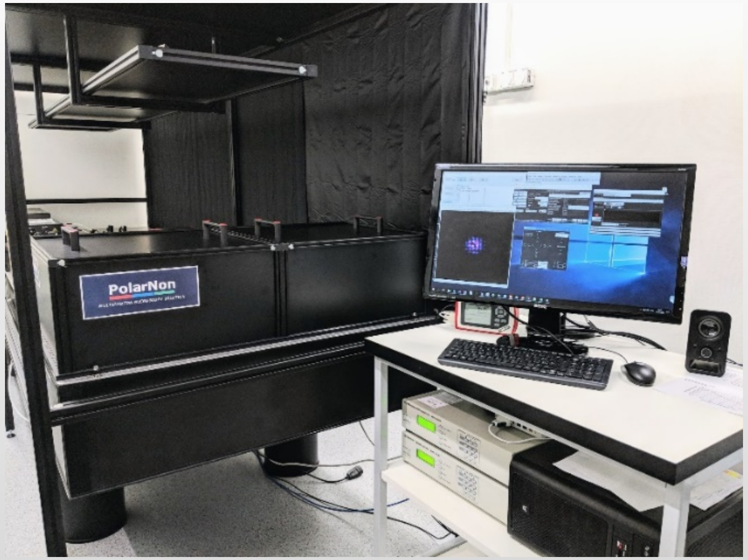
Understanding building blocks



20 - 100s nm

Diffraction limit

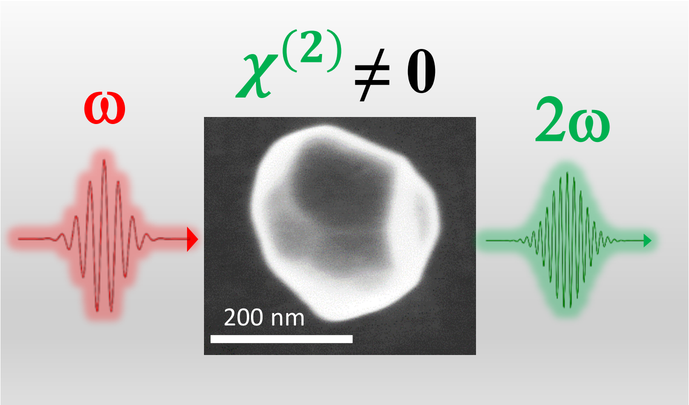
$$d = \frac{\lambda}{2\mathrm{NA}}$$



Super-resolution multiphoton polarimetric microscope

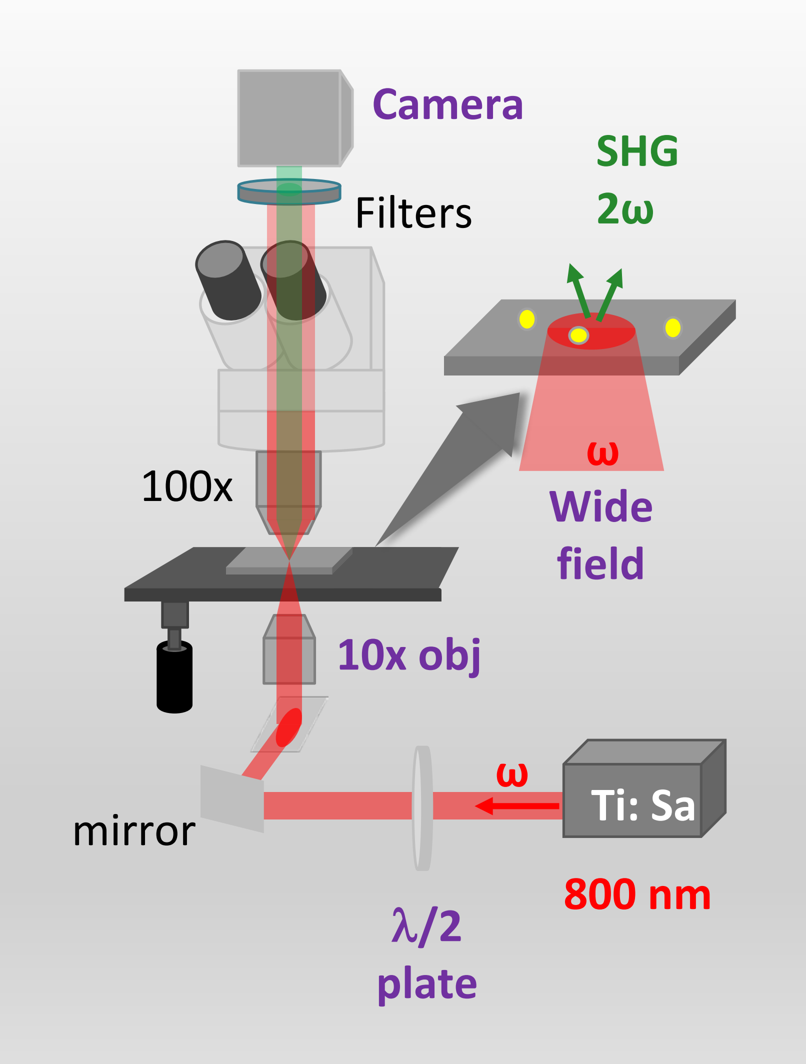
2018 competitors at the SPIE Europe Photonics Village in Strasbourg / Patent EP18193103.1

A powerful characterization tool



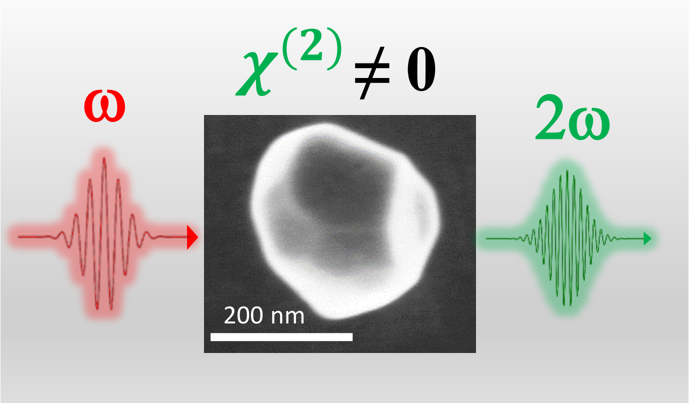
Diffraction limit

$$d = \frac{\lambda}{2\mathrm{NA}}$$



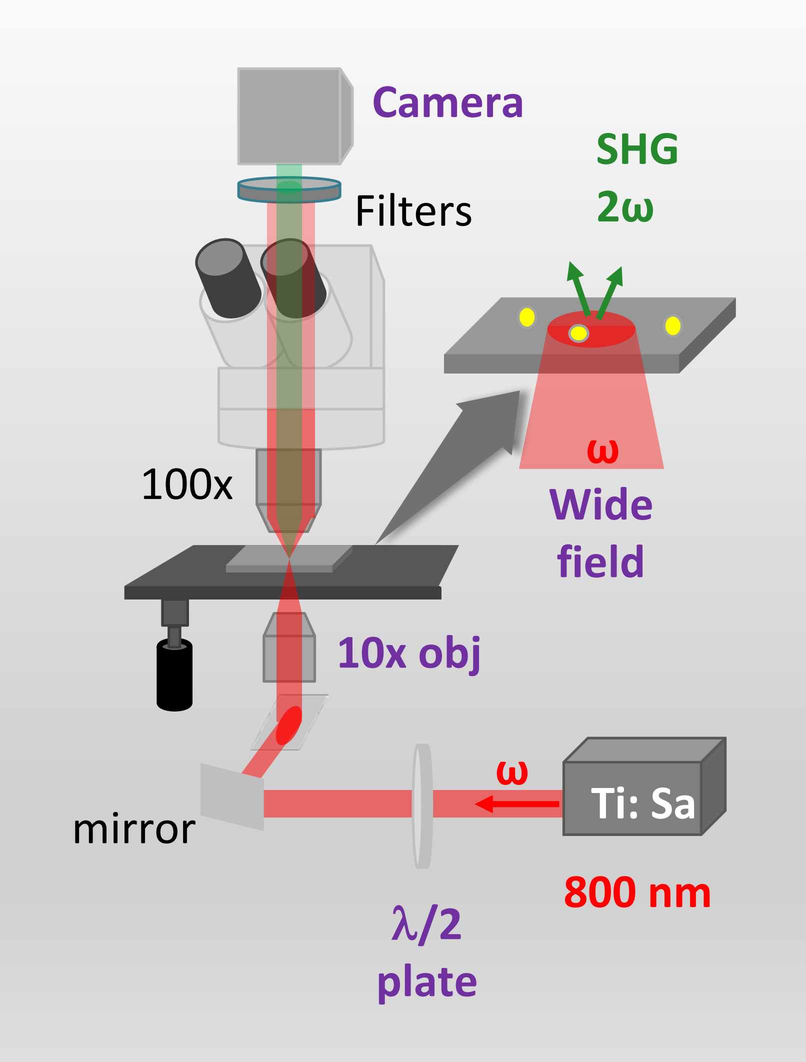
2018 competitors at the SPIE Europe Photonics Village in Strasbourg / Patent EP18193103.1

A powerful characterization tool



Diffraction limit

$$d = \frac{\lambda}{2\mathrm{NA}}$$

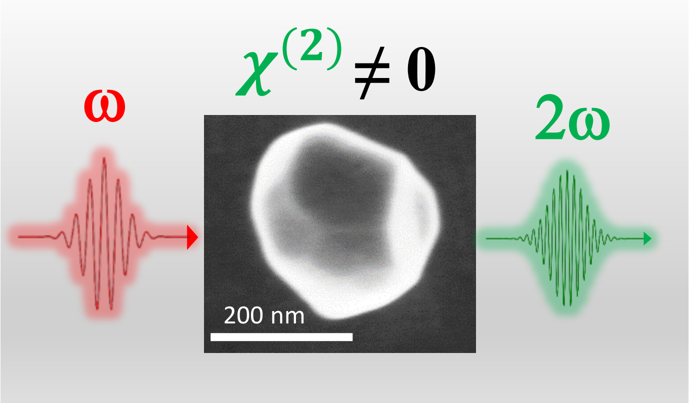


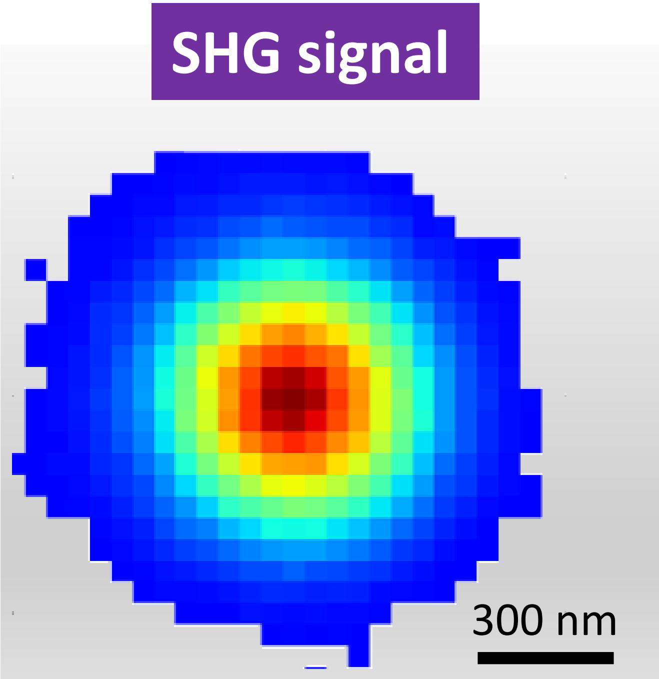
Special features

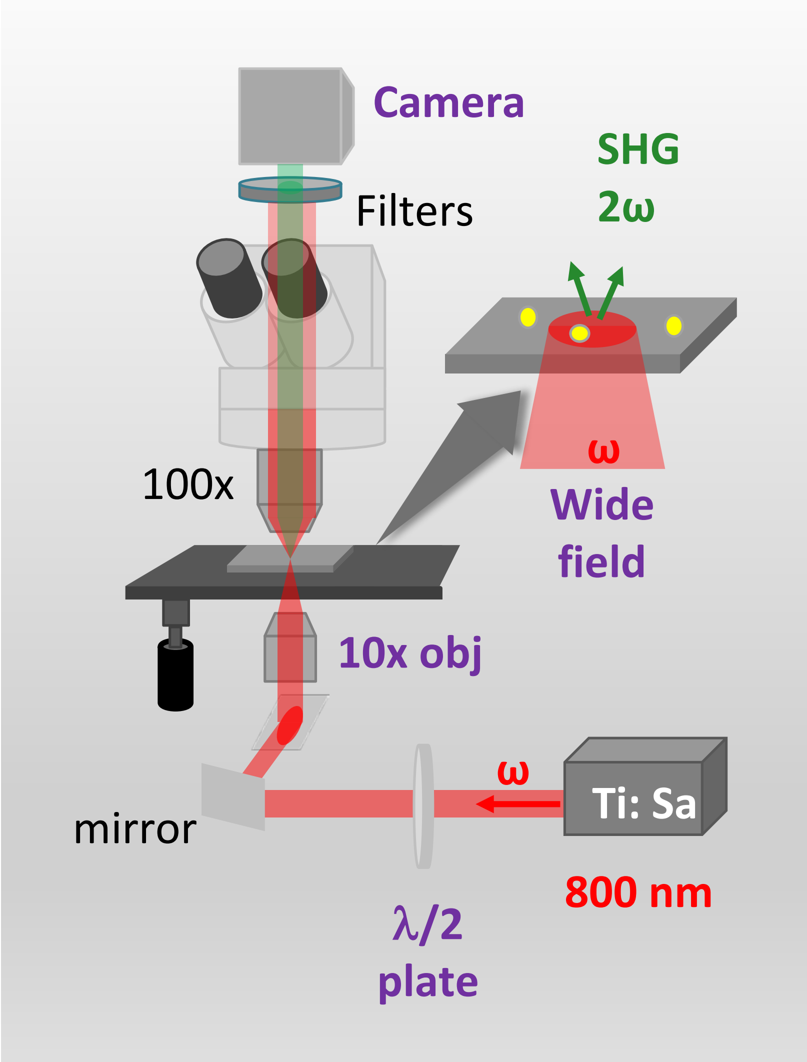
- Incident polarization rotation
- Wide field illumination
- Single pixel detection

2018 competitors at the SPIE Europe Photonics Village in Strasbourg / Bridge Funding

A powerful characterization tool

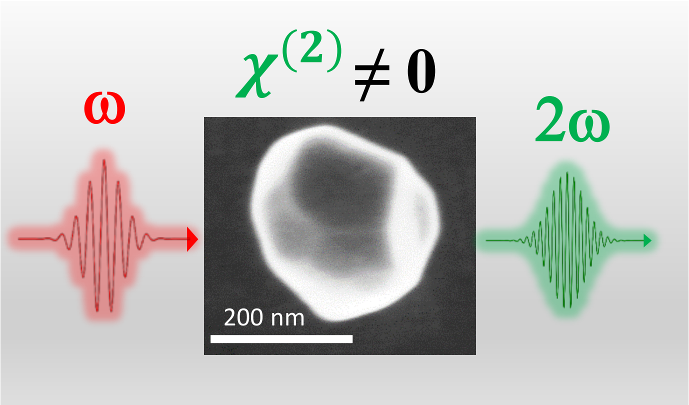




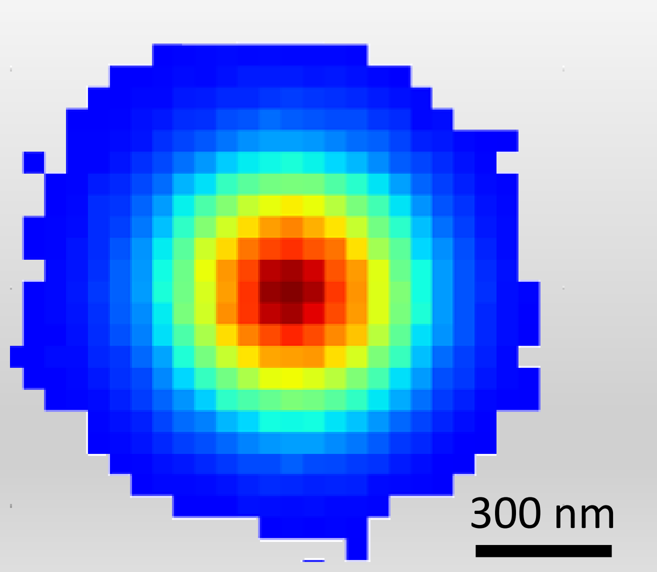


2018 competitors at the SPIE Europe Photonics Village in Strasbourg / Bridge Funding

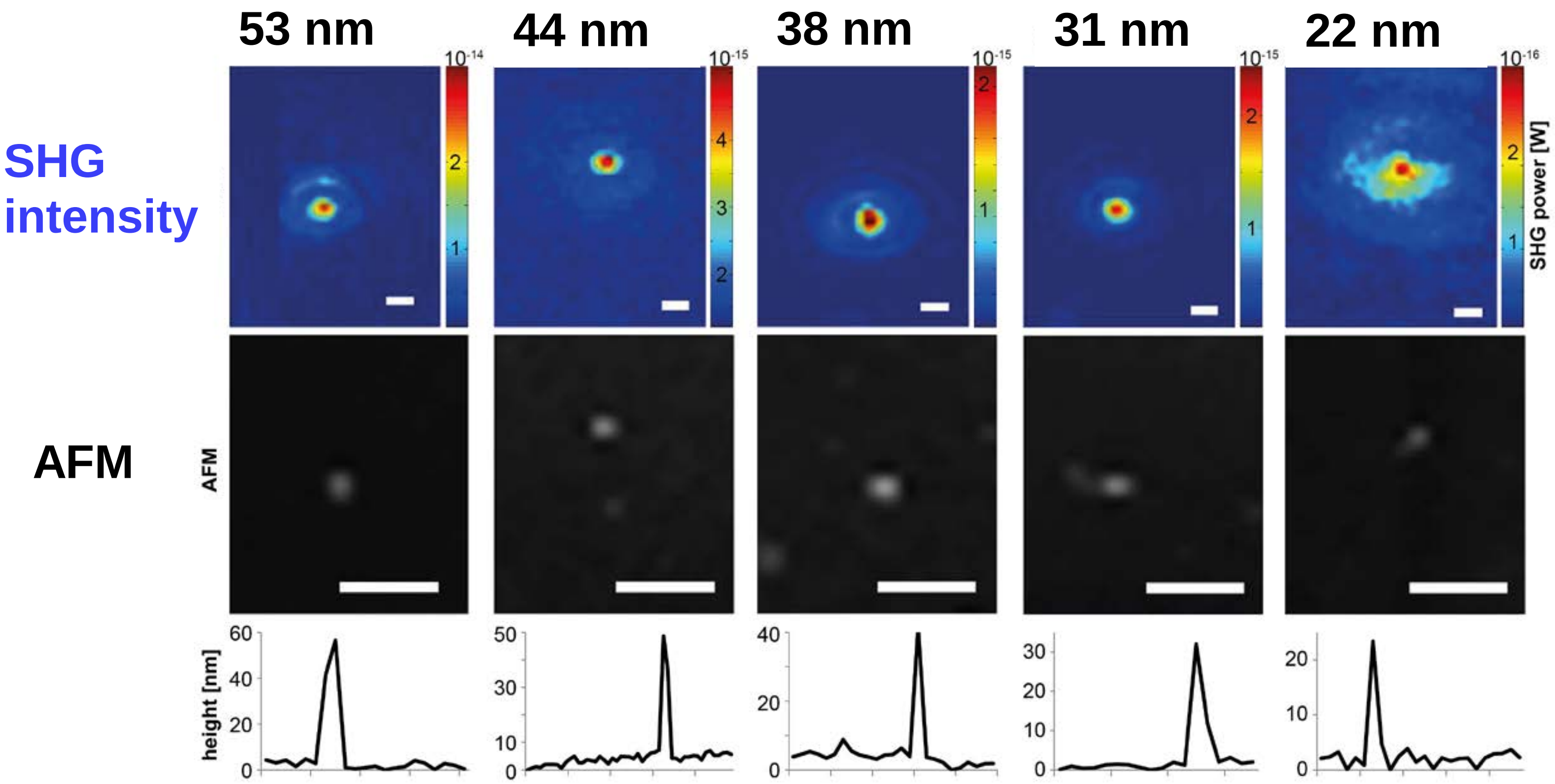
Average SHG intensity of single particles



SHG signal

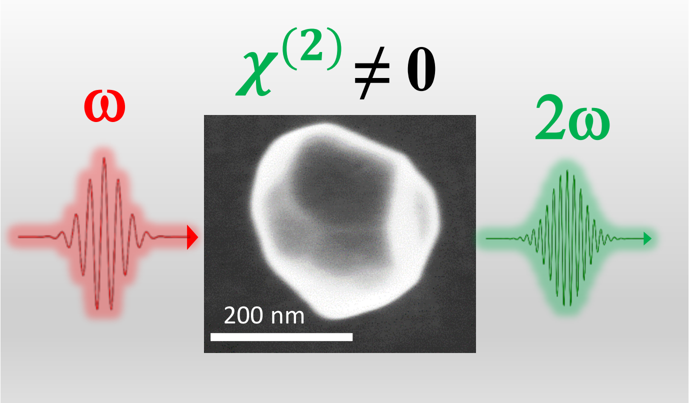


$BaTiO_3$ particles with diameters of :

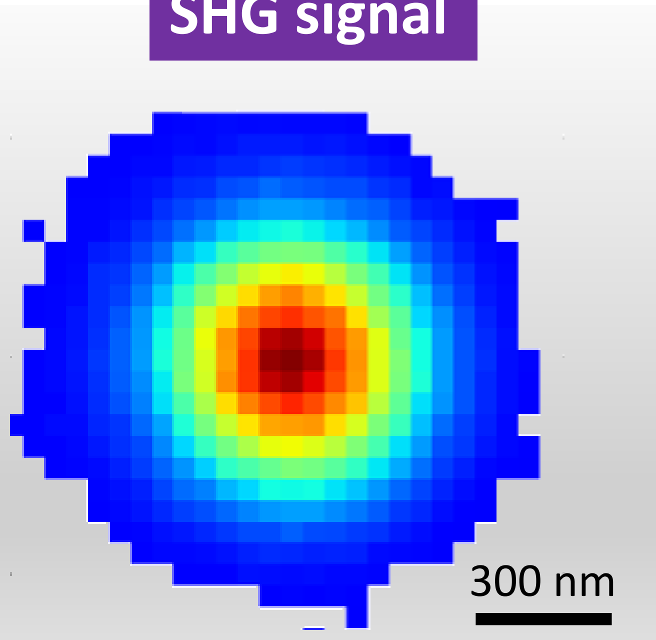


E. Kim, A. Steinbrück, M. T. Buscaglia, V. Buscaglia, T. Pertsch, and R. Grange, ACS Nano 7, 5343–5349, **2013.**

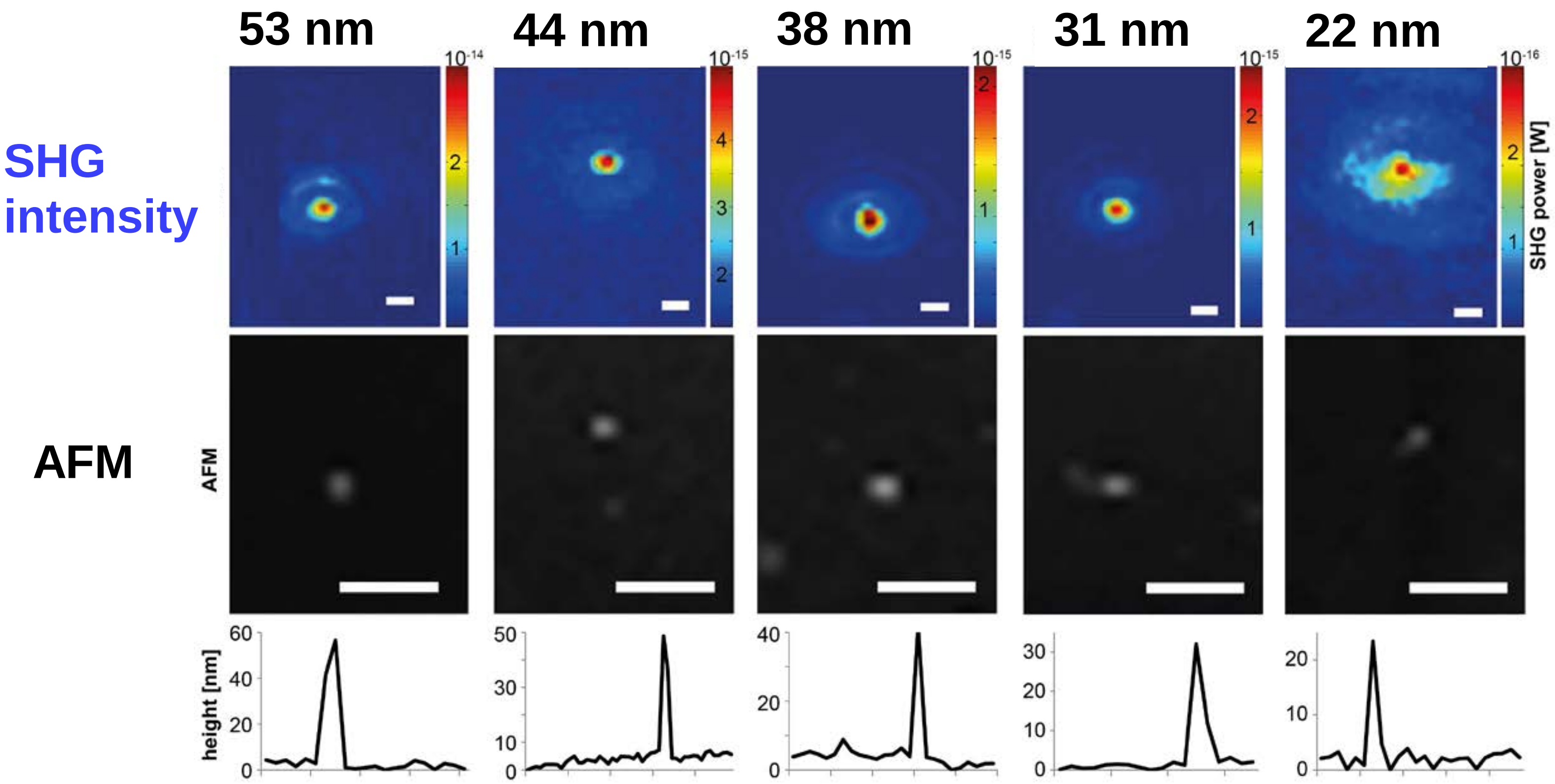
Average SHG intensity of single particles



SHG signal



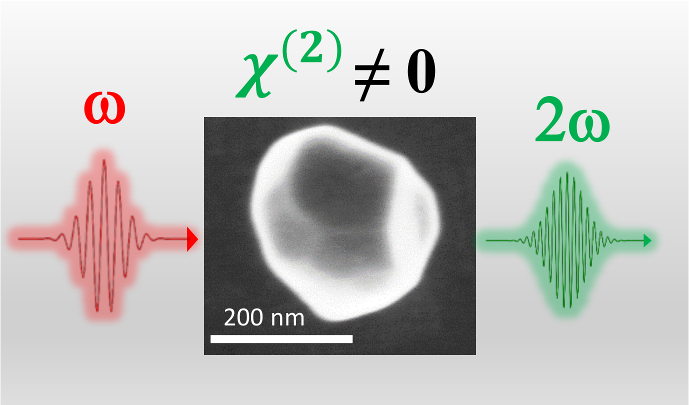
BaTiO$_3$ particles with diameters of :

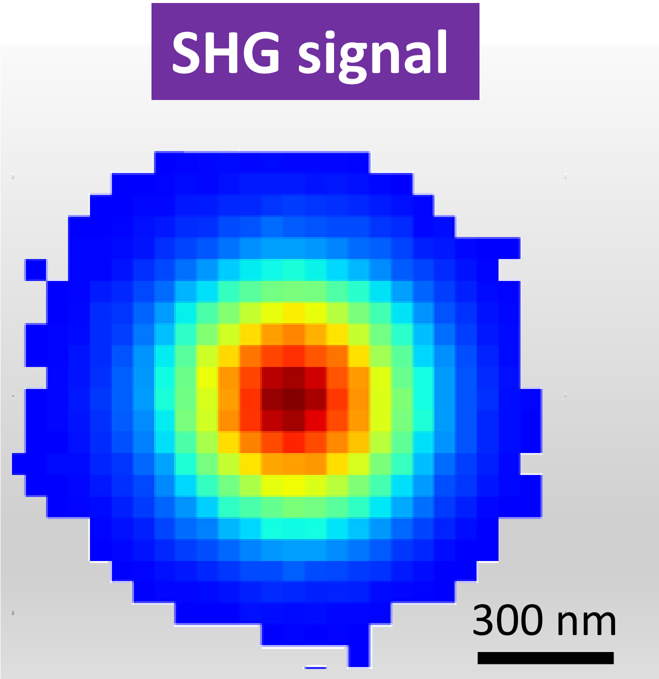


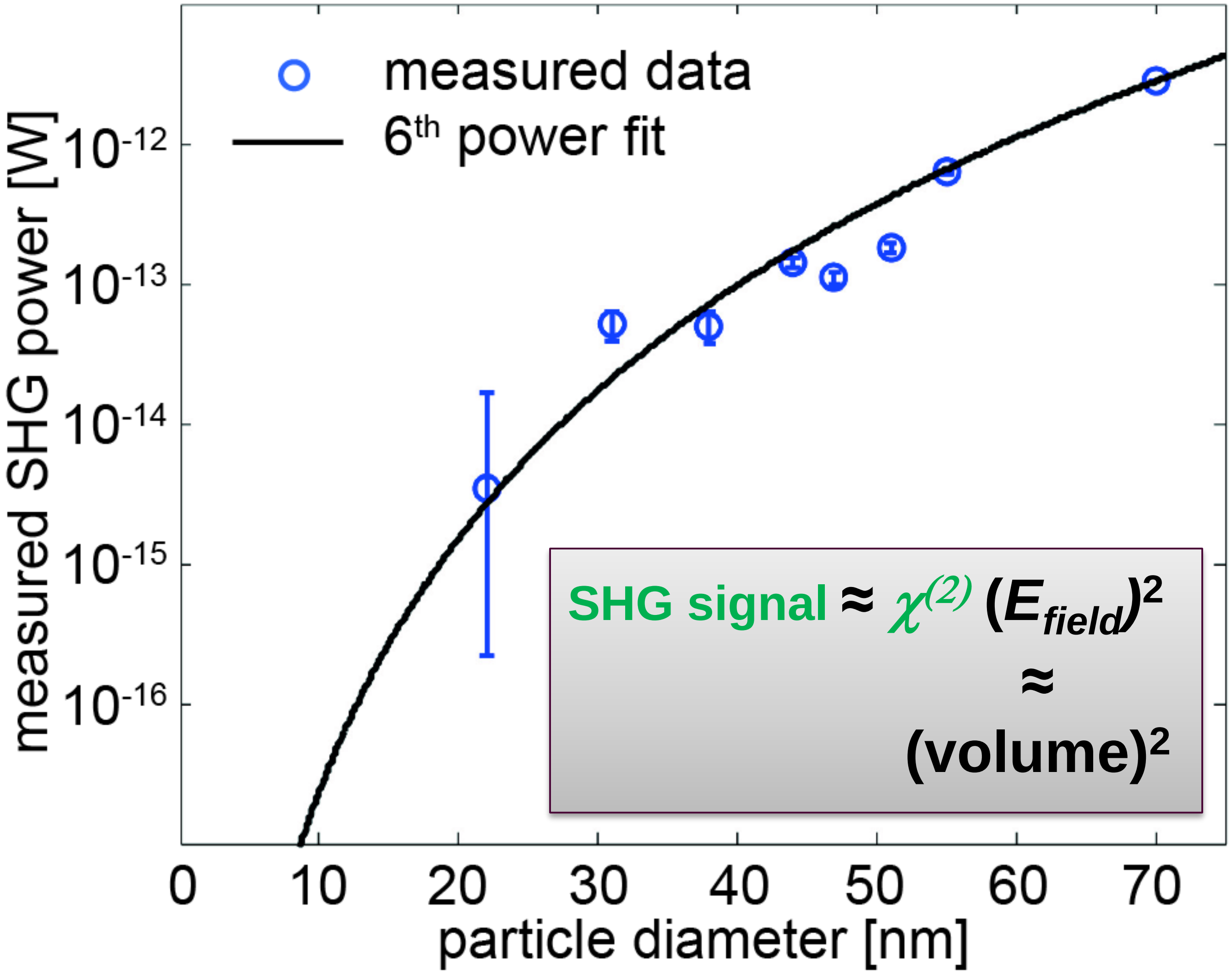
Particles are bright down to 20 nm...

E. Kim,...,and R. Grange, ACS Nano 7, 5343–5349, **2013.**
M. Timofeeva,..., R. Grange Nano Lett.,16, 6290, 2016.

Average SHG intensity of single particles







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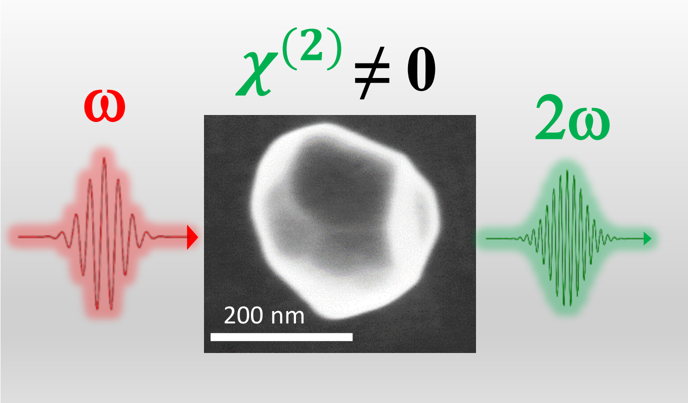

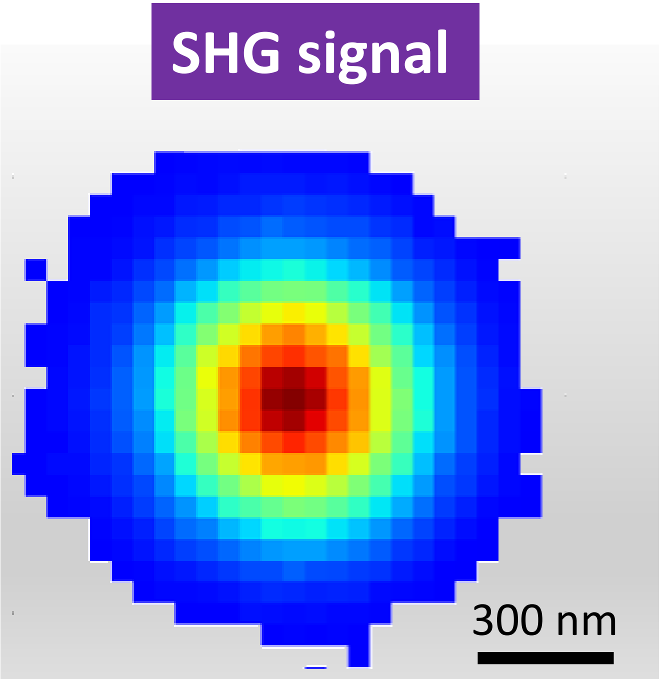

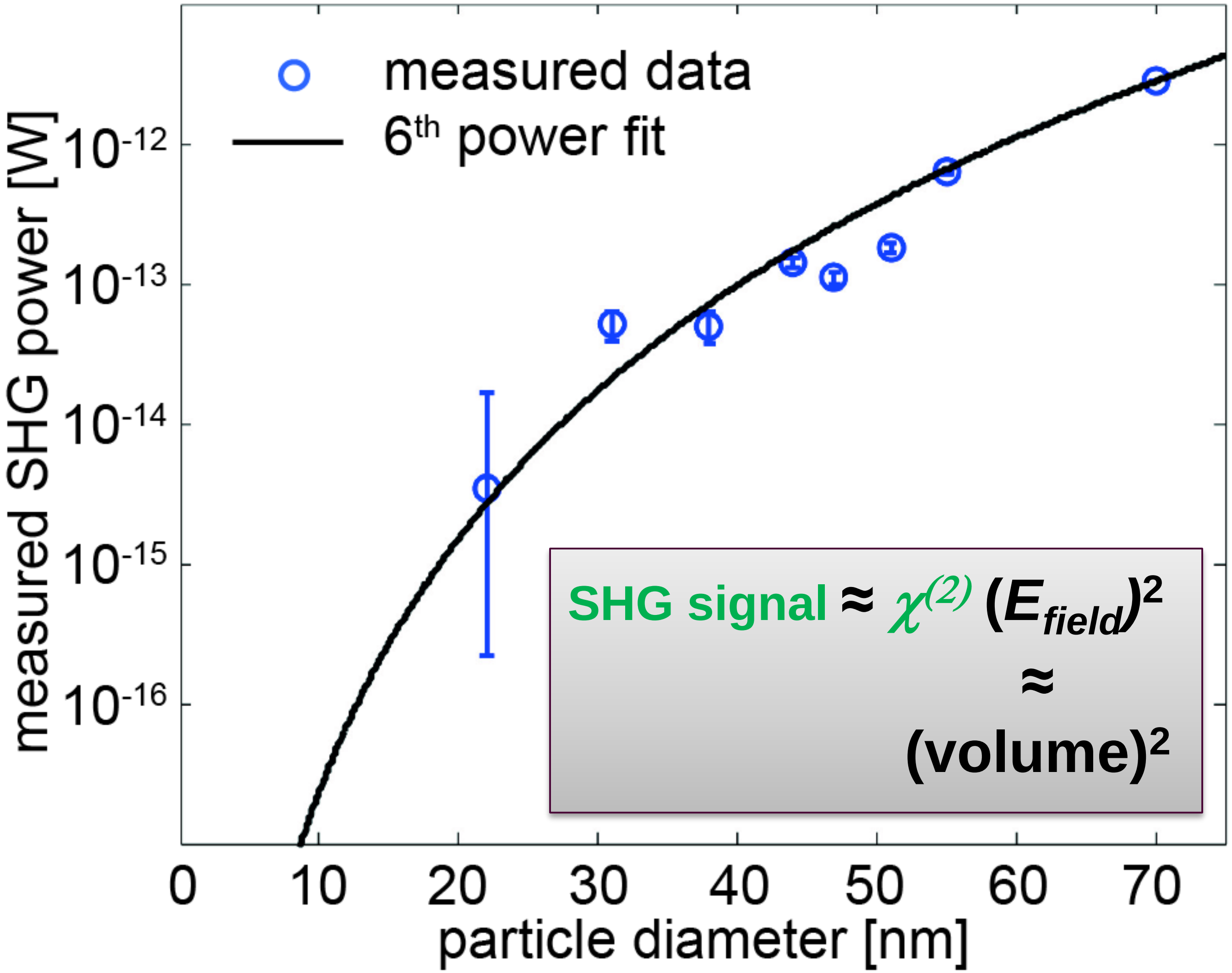

... room for improvements

E. Kim,…,and R. Grange, ACS Nano 7, 5343–5349, **2013.**
M. Timofeeva,…, R. Grange Nano Lett.,16, 6290, 2016.

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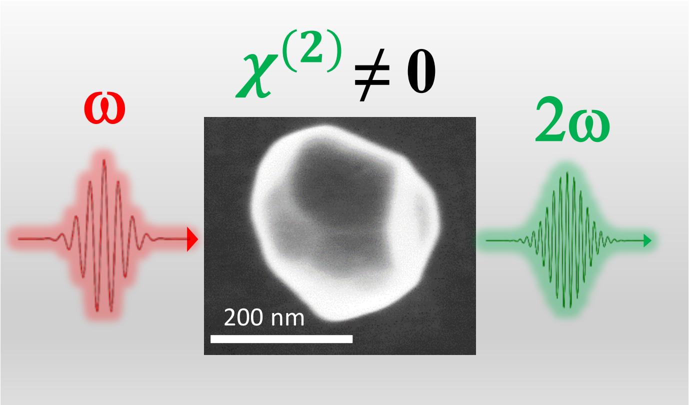

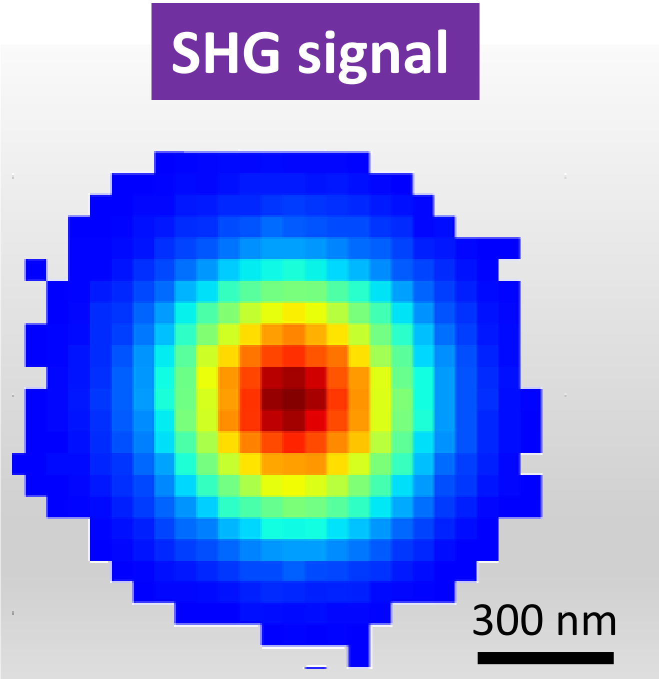

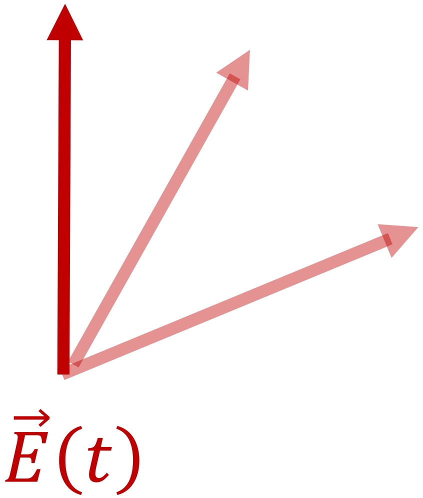

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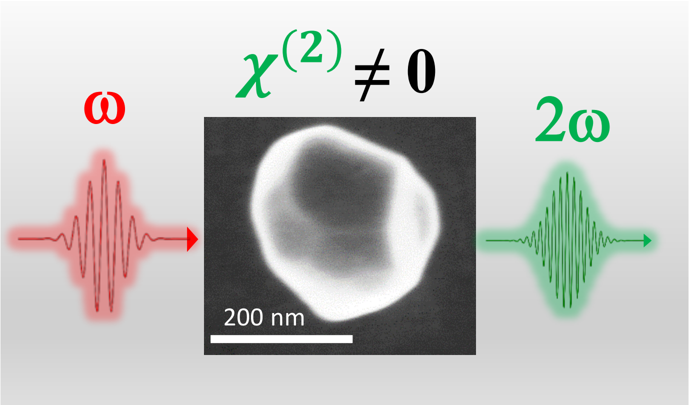
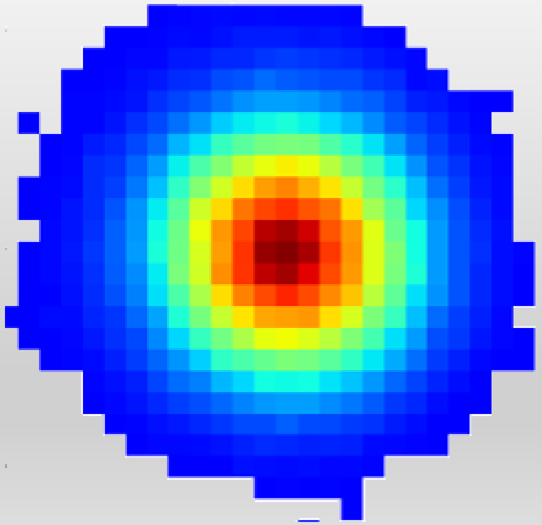


SHG signal



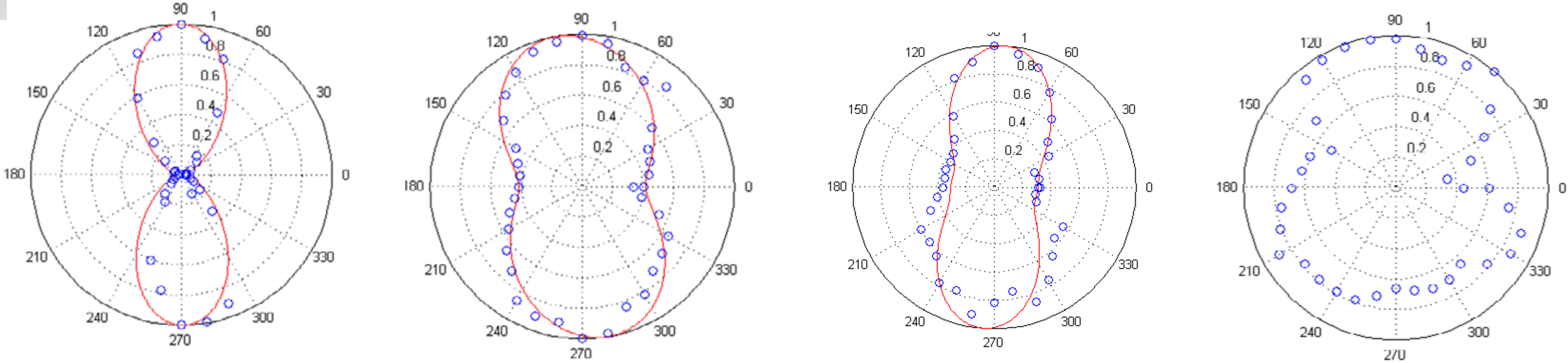
Average response over a single particle

$$\vec{P} = \varepsilon_0 \chi^{(1)} \vec{E} + \varepsilon_0 \boldsymbol{\chi}^{(2)} \vec{E}^2 + \cdots$$

Bulk fit

Measured value

53 nm | **D = 44 nm** | **D = 31 nm** | **D = 22 nm**



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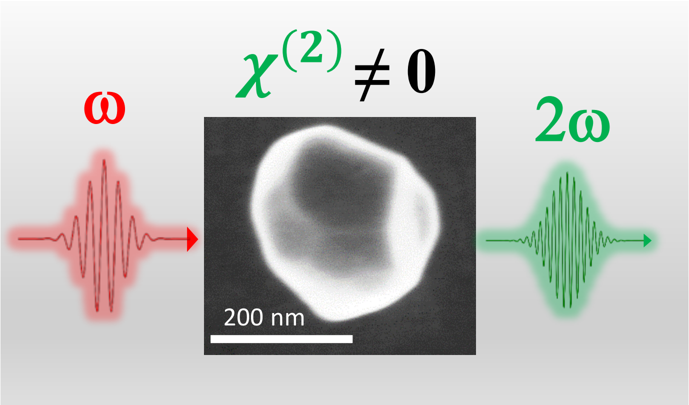

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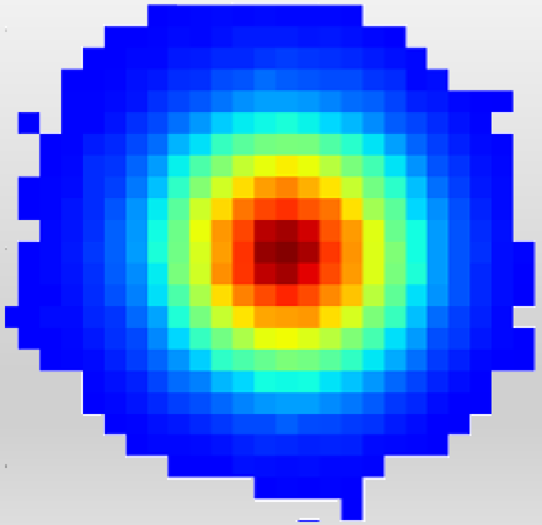

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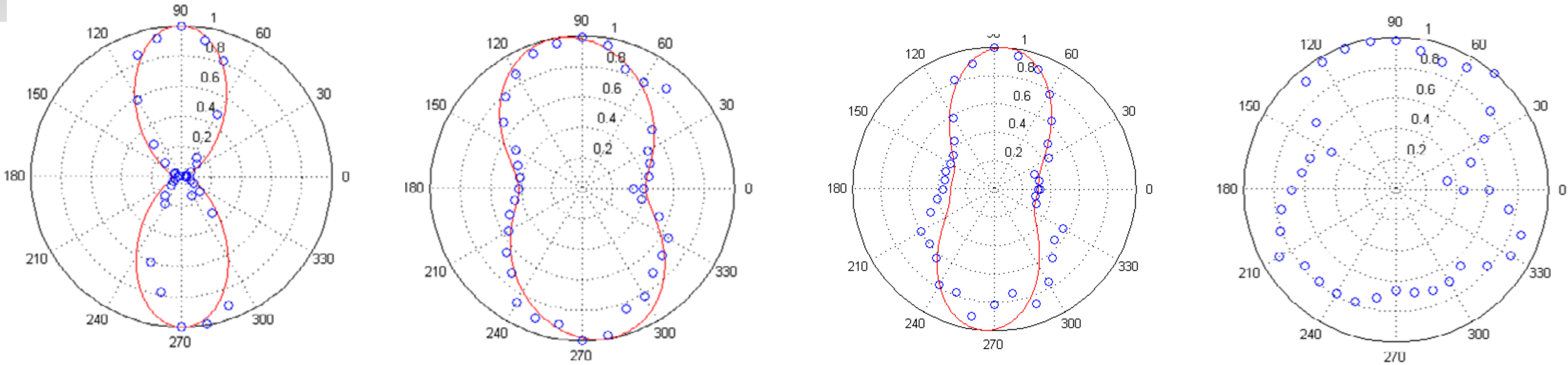
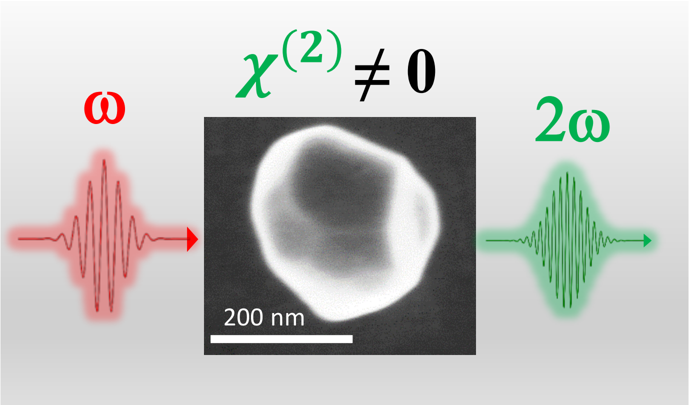


Uncertain crystallography for small particle sizes

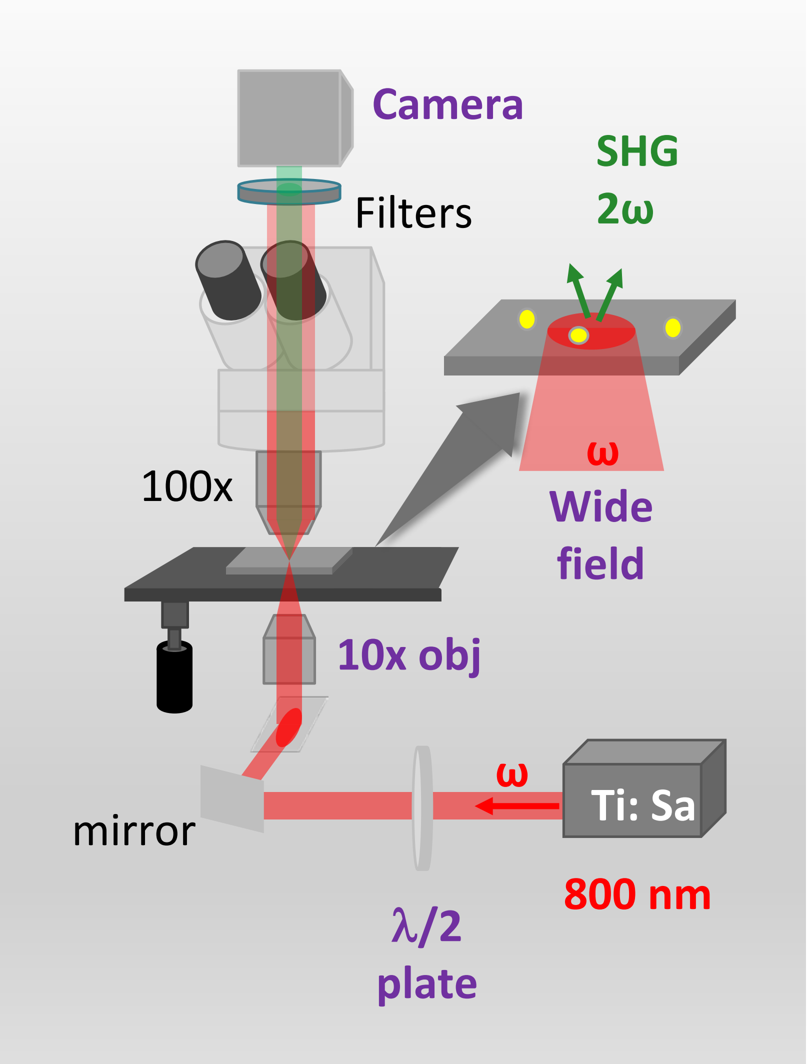
E. Kim,...,and R. Grange, ACS Nano 7, 5343–5349, **2013.**
M. Timofeeva,..., R. Grange Nano Lett.,16, 6290, 2016.

A powerful characterization tool

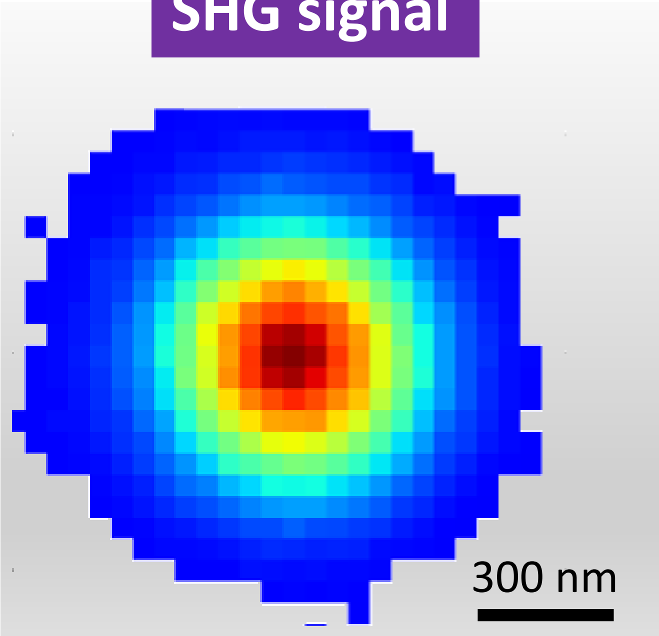


SHG intensity is a fourth power dependence

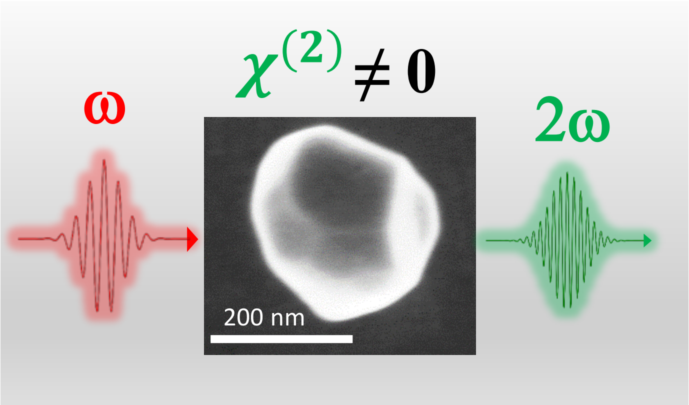
$$I(\alpha) \propto \left| \chi^{(2)} : E(\alpha) E(\alpha) \right|^2$$



SHG signal



A powerful characterization tool



SHG intensity is a fourth power dependence

$$I(\alpha) \propto \left|\chi^{(2)}: E(\alpha)E(\alpha)\right|^2$$

Decomposition into functions

$$I(\alpha)/I_0 \propto 1 + a_2 \cos 2\alpha + b_2 \sin 2\alpha + a_4 \cos 4\alpha + b_4 \sin 4\alpha$$

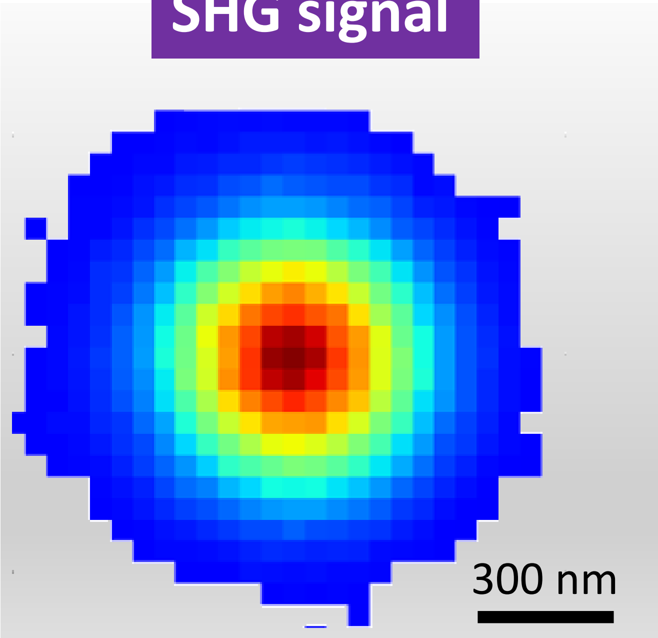
Amplitudes

$$I_2 = \sqrt{a_2^2 + b_2^2}, \quad I_4 = \varepsilon_4 \sqrt{a_4^2 + b_4^2}$$

Orientations

$$\varphi_2 = \frac{1}{2} \arctan \frac{b_2}{a_2}, \quad \varphi_4 = \frac{1}{4} \arctan \frac{b_4}{a_4}$$

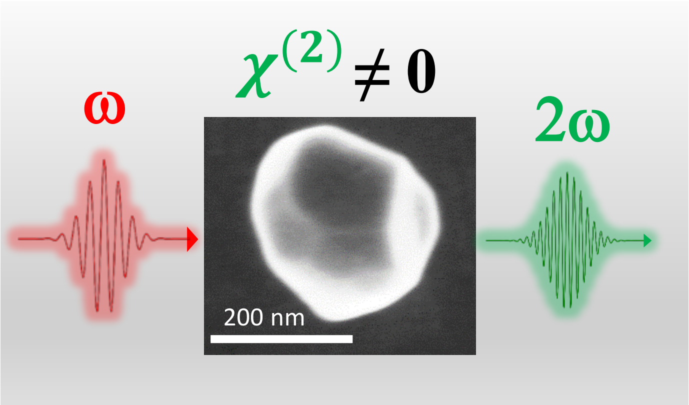
SHG signal



Collaboration with Sophie Brasselet, Inst. Fresnel

Rendon, Timpu, Grange, Brasselet, Scientific report, Accepted, 2018

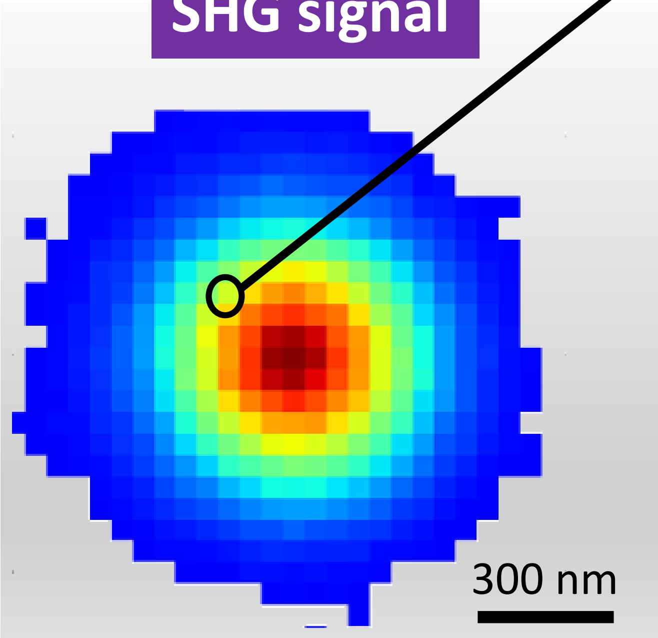
Super-resolution multiphoton polar microscope

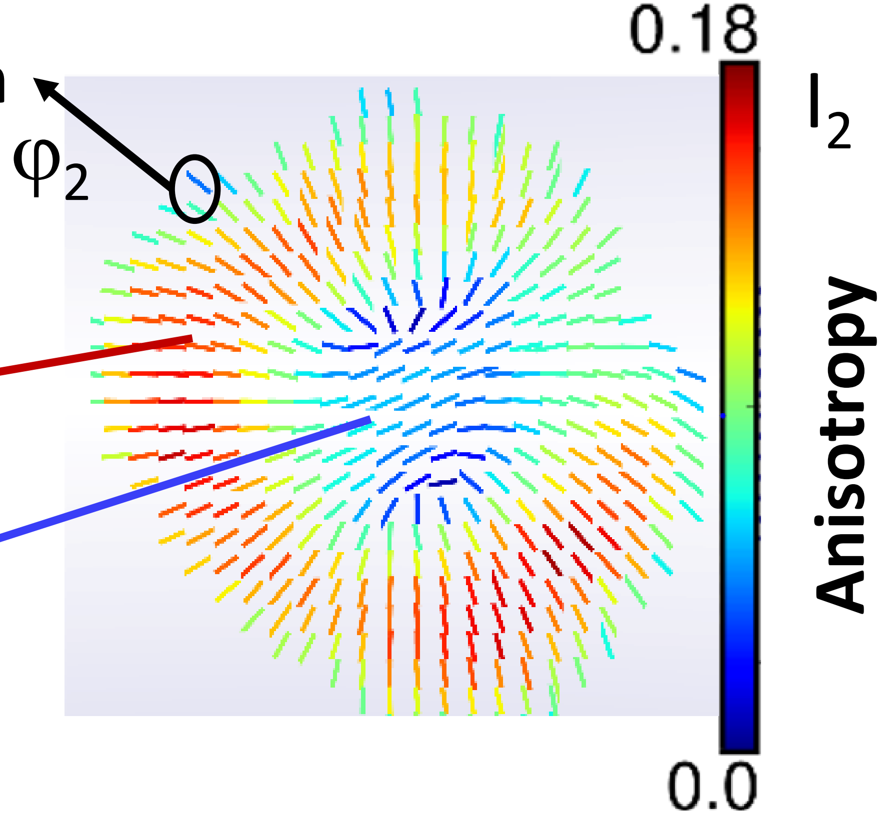


Single pixel analysis

1 pixel = 50 nm

SHG signal





Cubic at the surface

Tetragonal core

Collaboration with Sophie Brasselet, Inst. Fresnel

Rendon, Timpu, Grange, Brasselet, Scientific report, Accepted, 2018

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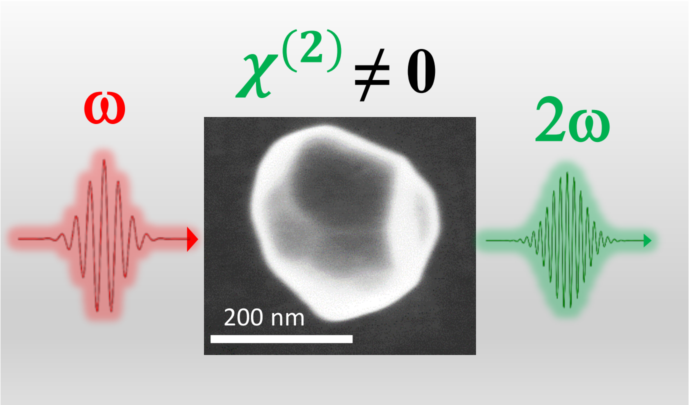

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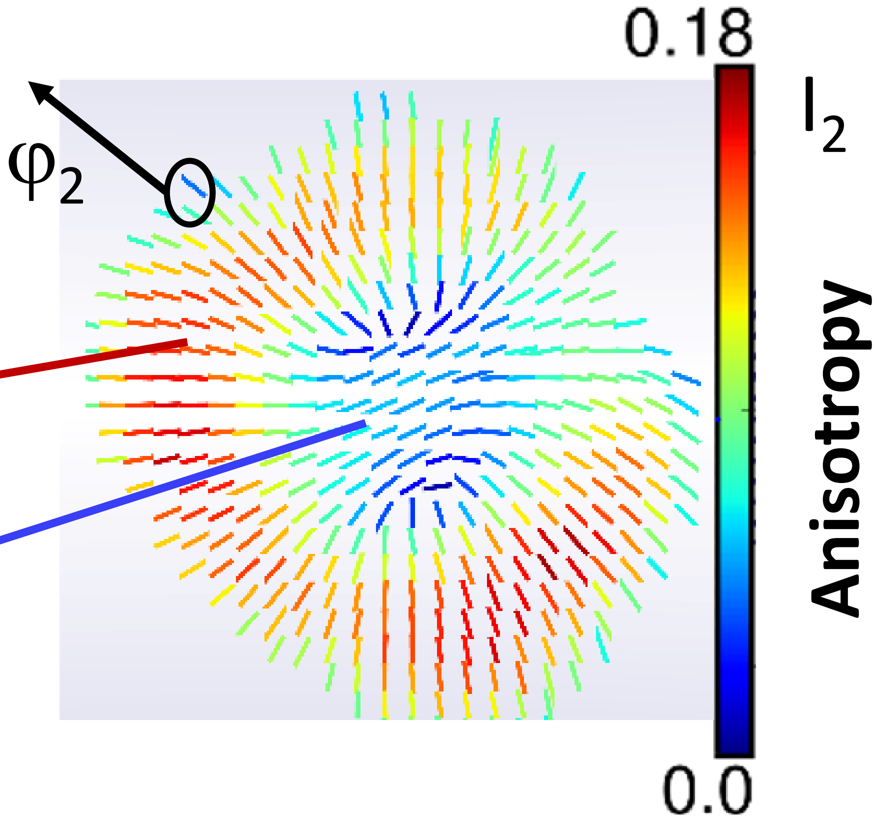

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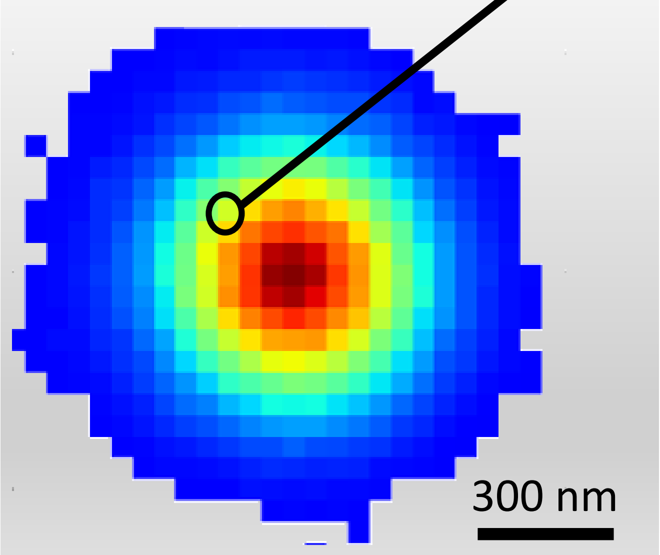


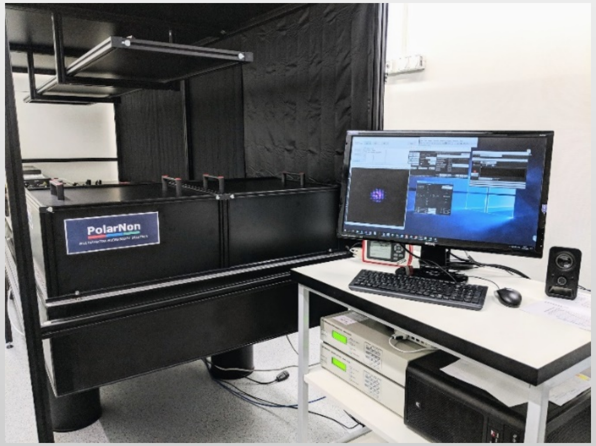
Solve the crystal uncertainty with an optical microscope

Collaboration with Sophie Brasselet, Inst. Fresnel

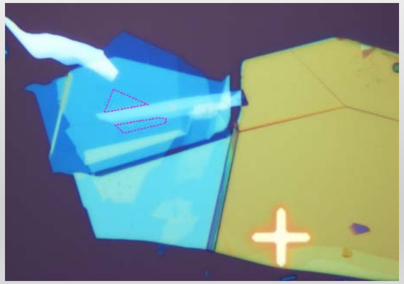
Rendon, Timpu, Grange, Brasselet, Scientific report, Accepted, 2018

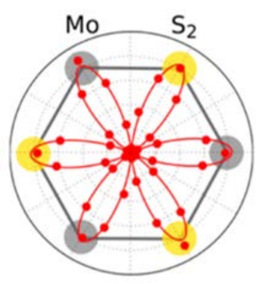
Super-resolution polar multiphoton microscope

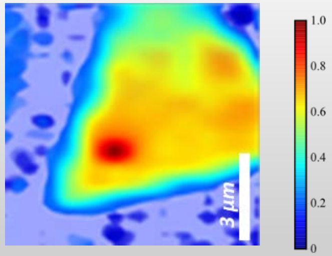
Super-resolution polar multiphoton microscope

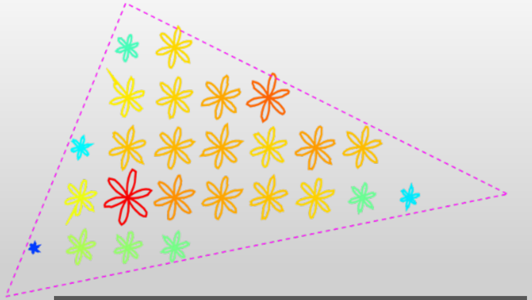


2D materials layers orientation



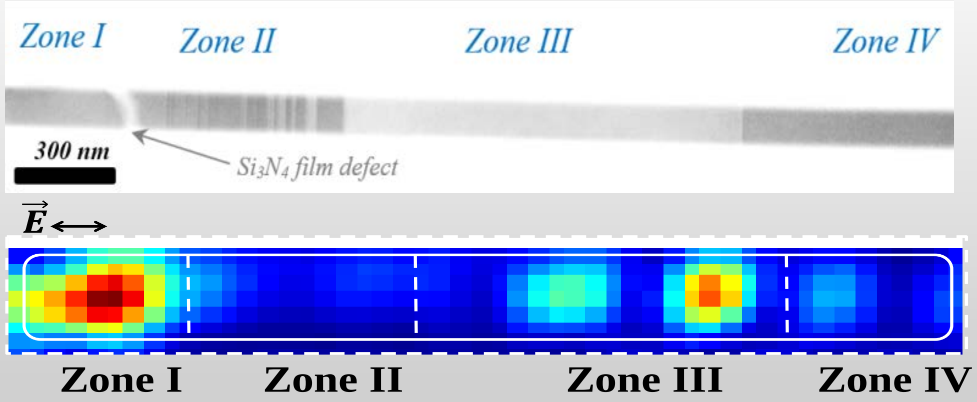




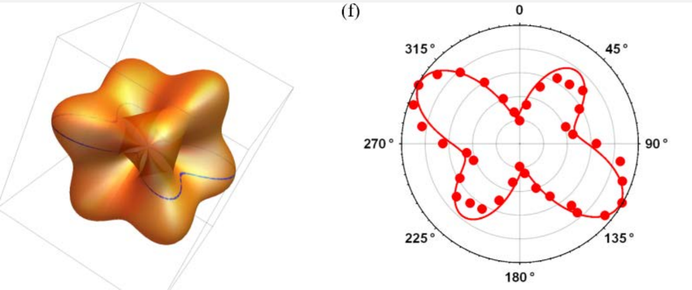


MoS2 sample from K. Ensslin

Crystal structures along III-V nanowires



Zone III

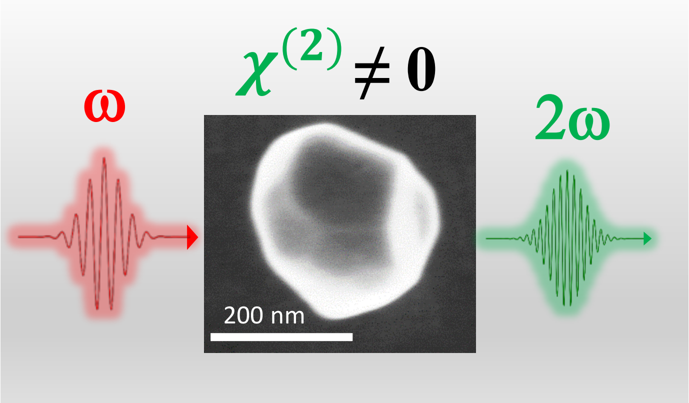


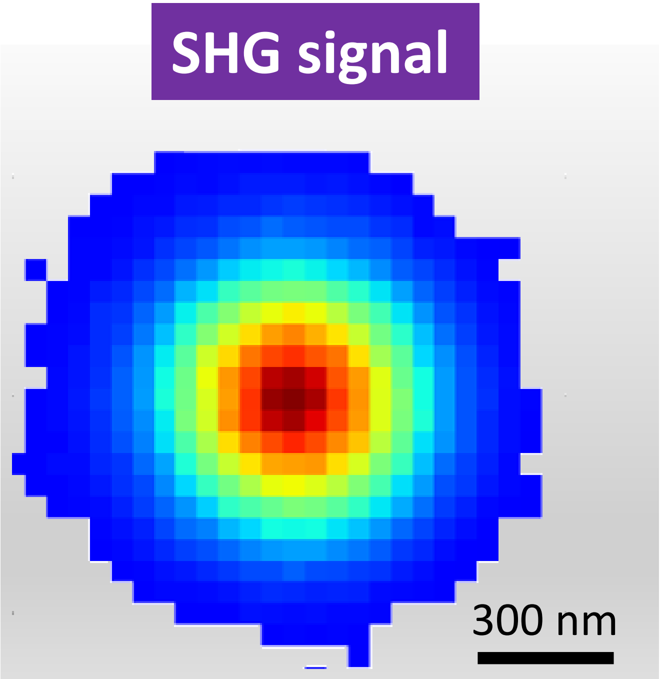
Pure Zinc Blend

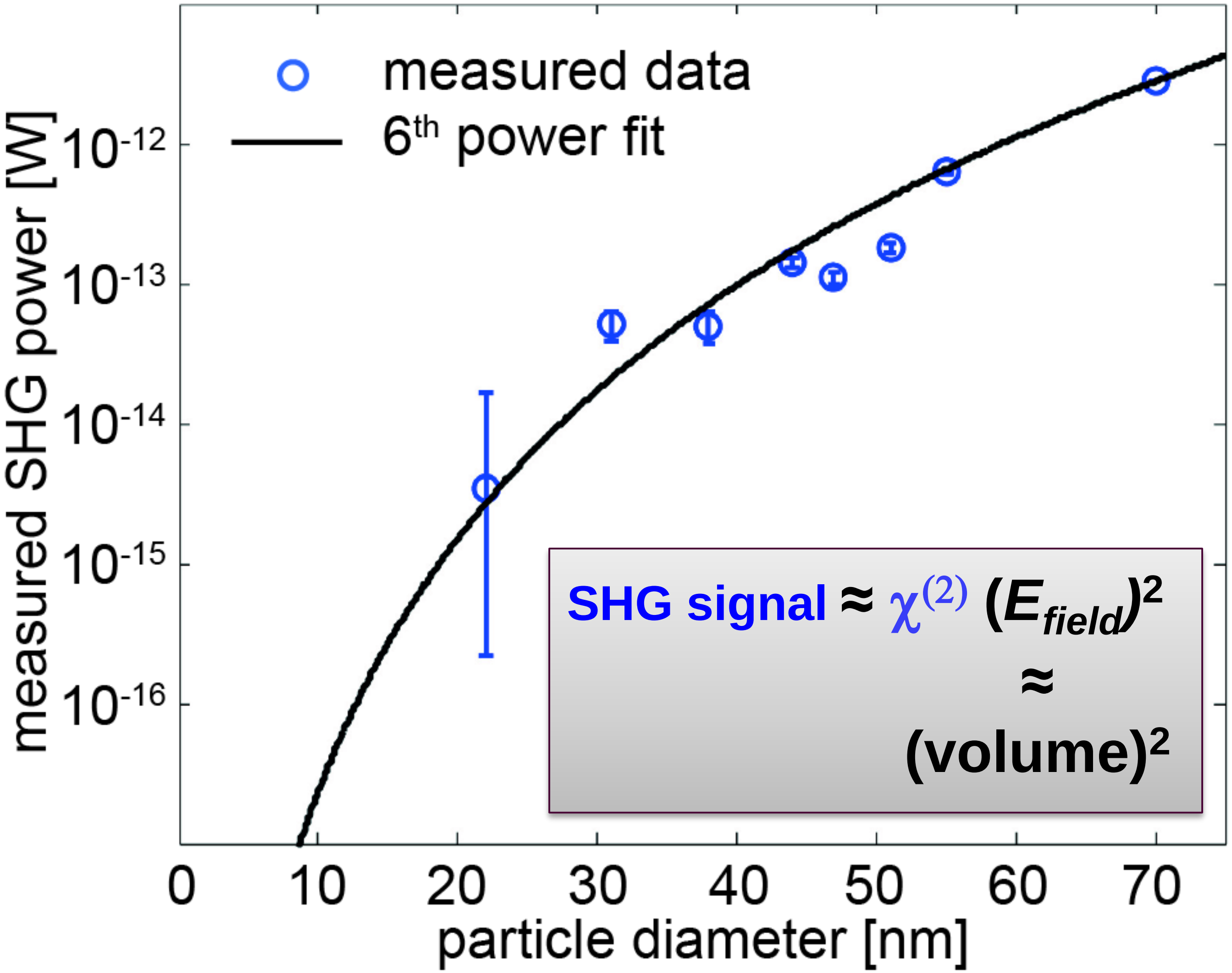
Grange, R *et al. Nano letters 12,* **2012**

M. Timofeeva,…, R. Grange Nano Lett.,16, 6290, 2016.

Average SHG intensity of single particles







SHG signal ≈ $\chi^{(2)}$ $(E_{field})^2$ ≈ $(\text{volume})^2$

... room for improvements

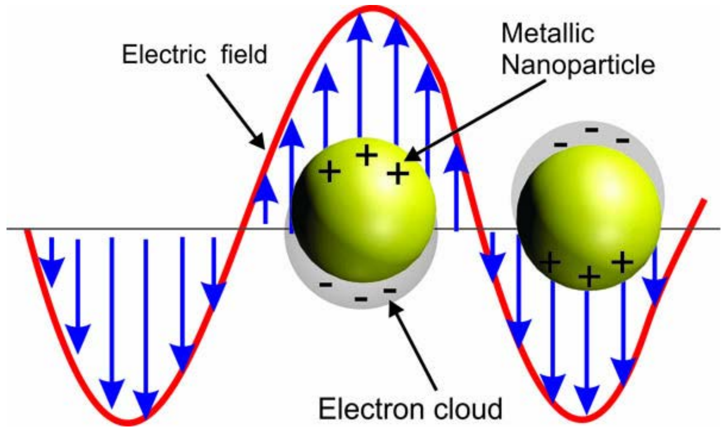
E. Kim,...,and R. Grange, ACS Nano 7, 5343–5349, **2013.**
M. Timofeeva,..., R. Grange Nano Lett.,16, 6290, 2016.

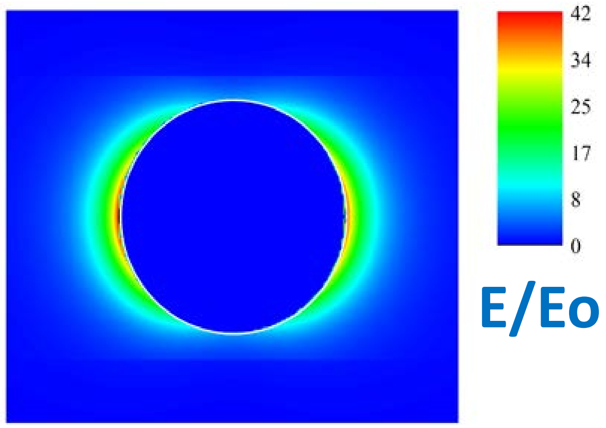
Strategies to enhance nonlinear optical signals

- **with plasmonics**
- with the $\chi^{(2)}$ material itself

What is plasmonics ?

60 nm gold nanoparticles






Stained glass, Notre Dame de Paris , 1250

Conduction electrons can oscillate at the surface of the metal…

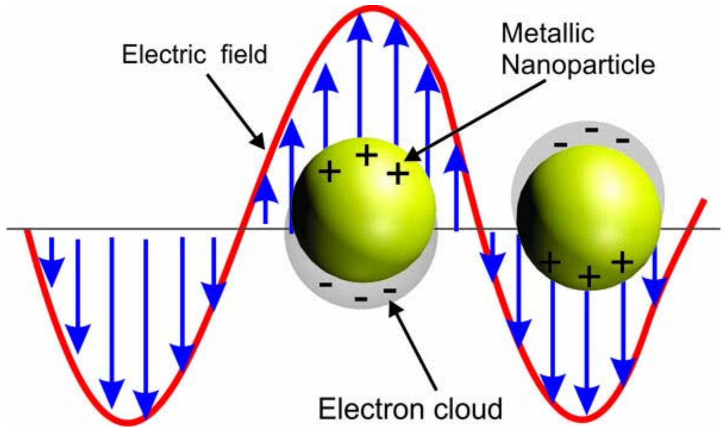
…generating strong resonance in the vicinity of the metal…

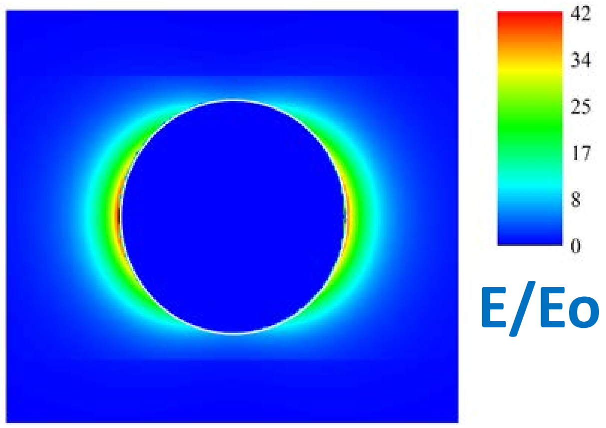
… at visible frequencies

El-Sayed, Atwater, Polman, Halas, Novotny, Fritsche, Aizpurua, …

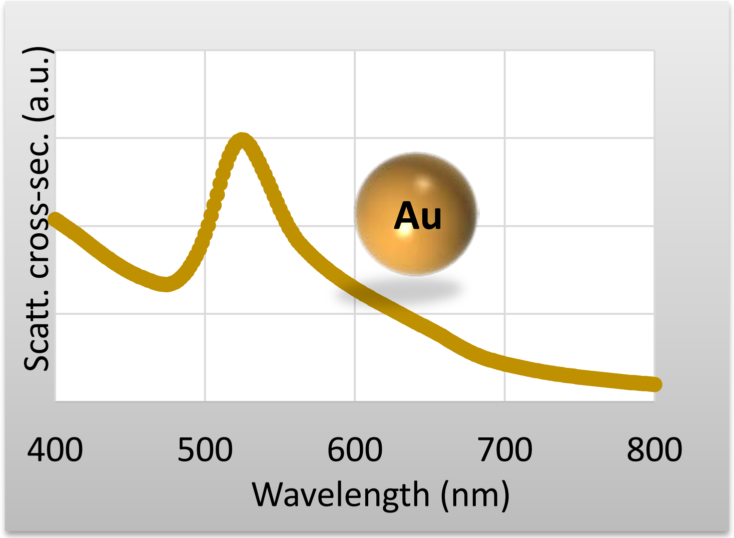
What is plasmonics ?

60 nm gold nanoparticles





Scattering cross-section



Conduction electrons can oscillate at the surface of the metal…

…generating strong resonance in the vicinity of the metal…

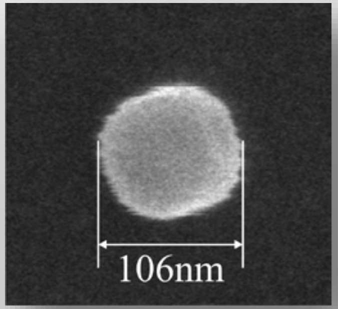
Single electric dipole resonance

El-Sayed, Atwater, Polman, Halas, Novotny, Fritsche, Aizpurua, …

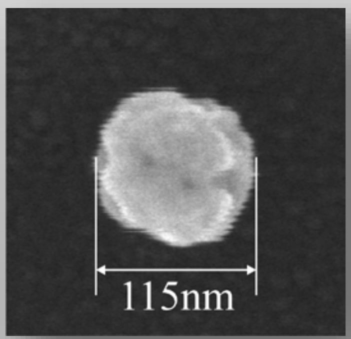
Combination of plasmonics with $\chi^{(2)}$ materials

$\chi^{(2)}$ material core + gold shell

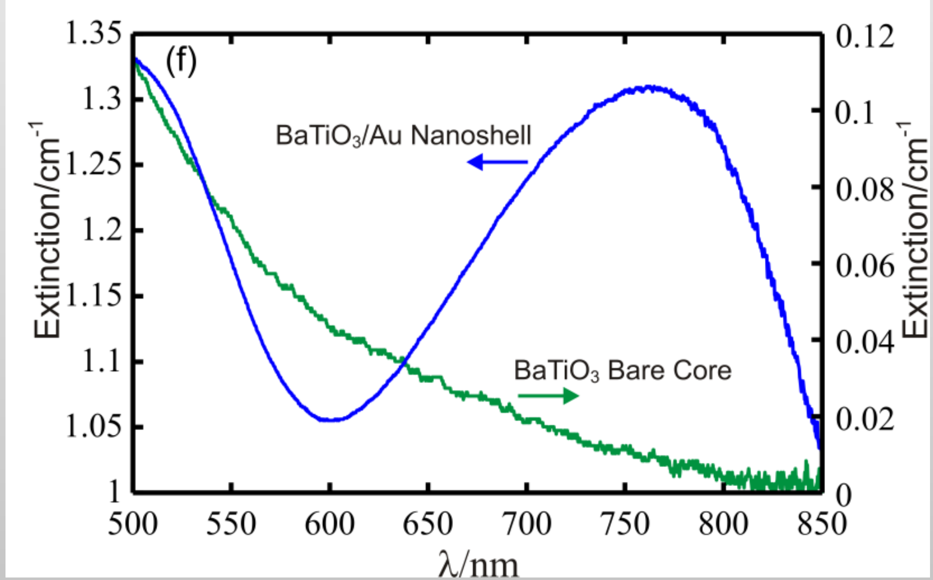
Bare $BaTiO_3$



Core-shell $BaTiO_3$

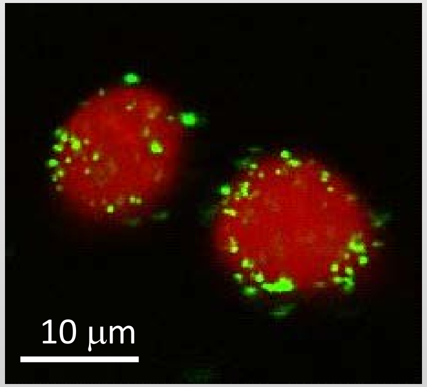


Extinction measurement in suspension



Y. Pu, R. Grange, Ch.-L. Hsieh, and D. Psaltis, Phys. Rev. Lett., 104, **2010**.

Bioimaging



Hsieh, Grange et al, Opt. Exp. **2009**
Hsieh, Grange et al, Biomaterials, **2010**
Grange et al., Biomedical Opt Exp, **2011**

SHG enhancement factor > 500

Combination of plasmonics with $\chi^{(2)}$ materials

$\chi^{(2)}$ material core + gold shell

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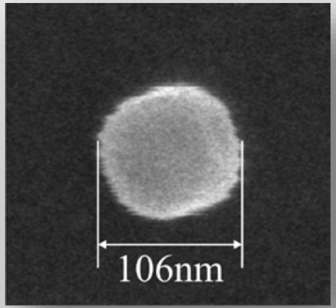
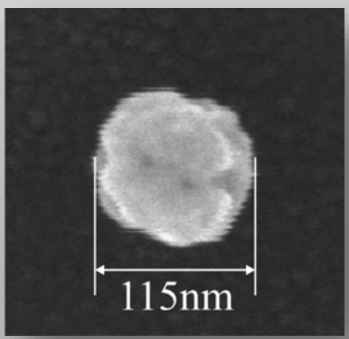
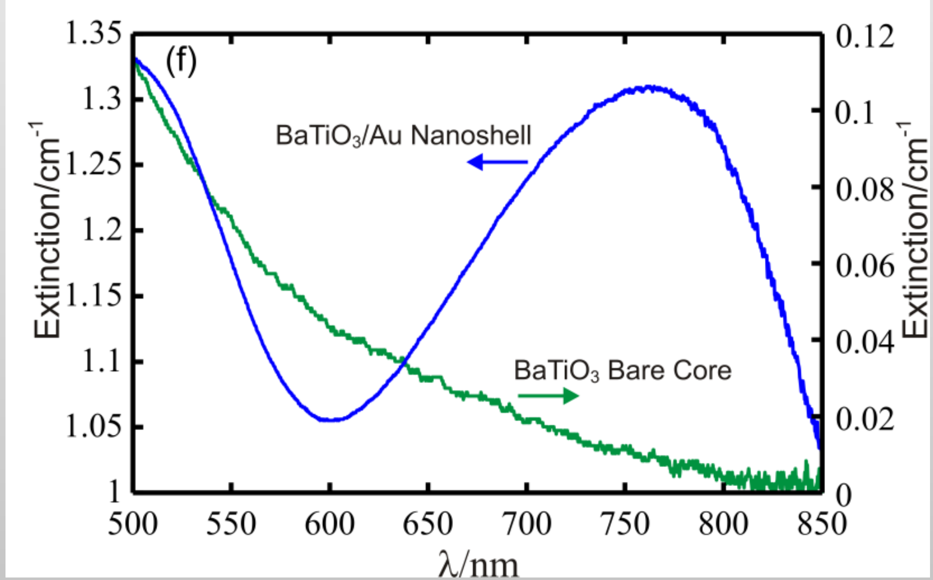


Core-shell $BaTiO_3$

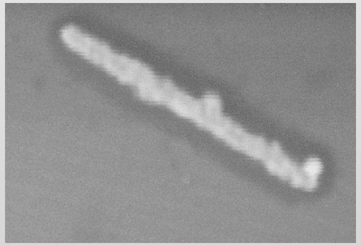


Extinction measurement in suspension



Y. Pu, R. Grange, Ch.-L. Hsieh, and D. Psaltis, Phys. Rev. Lett., 104, **2010**.

$KNbO_3$ nanowires



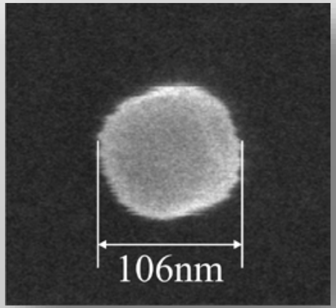
J. Richter,…, R. Grange Nanoscale, 6, 5200, 2014.

SHG enhancement factor > 250

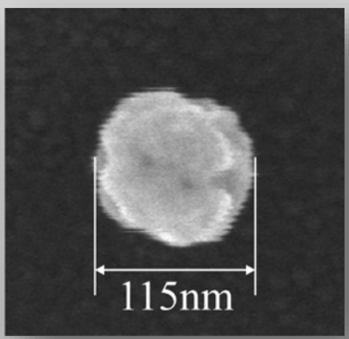
Combination of plasmonics with $\chi^{(2)}$ materials

$\chi^{(2)}$ material core + gold shell

Bare $BaTiO_3$



Core-shell $BaTiO_3$



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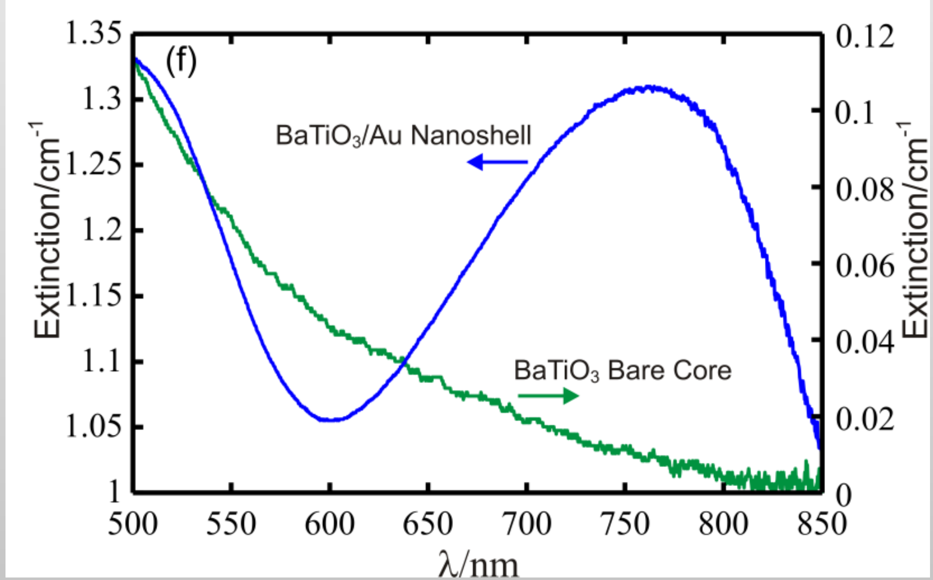

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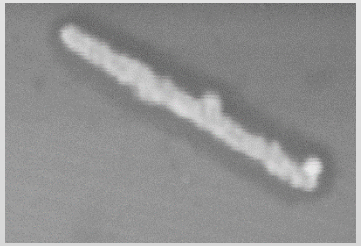


J. Richter,..., R. Grange
Nanoscale, 6, 5200, 2014.

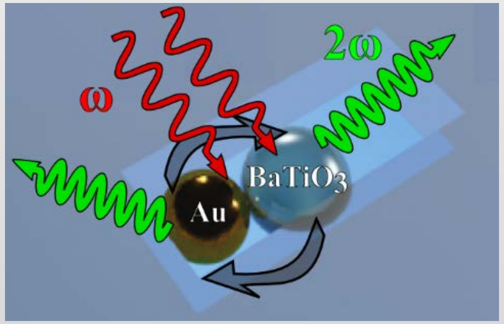
SHG enhancement factor > 250

Markers as bright as quantum dots, no bleaching, and biocompatible

Combination of plasmonics with $\chi^{(2)}$ materials

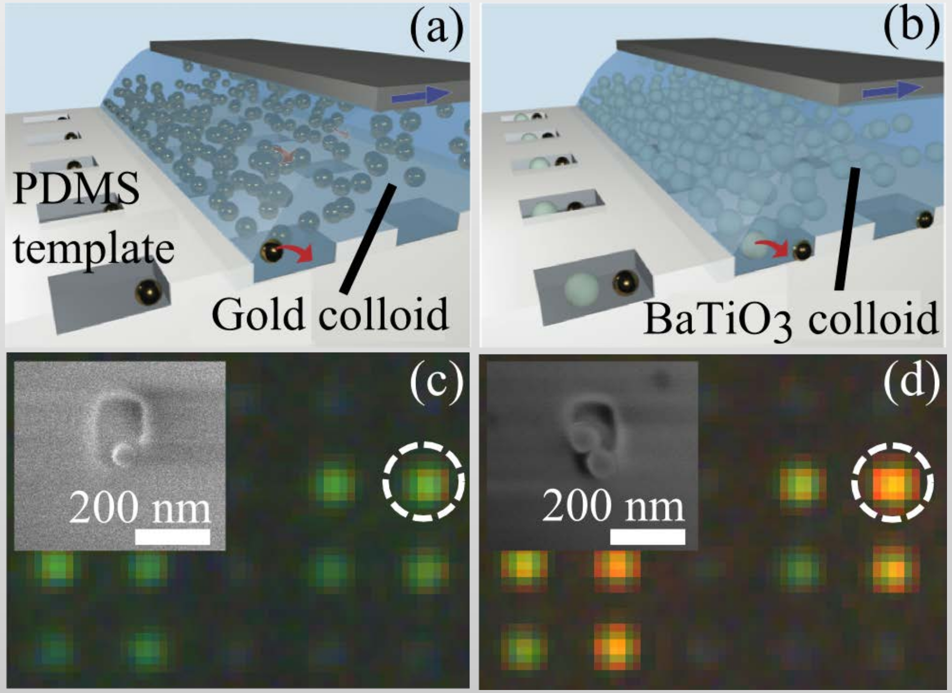
Sequential Capillarity-Assisted Particle Assembly

Hybrid Nanodimers

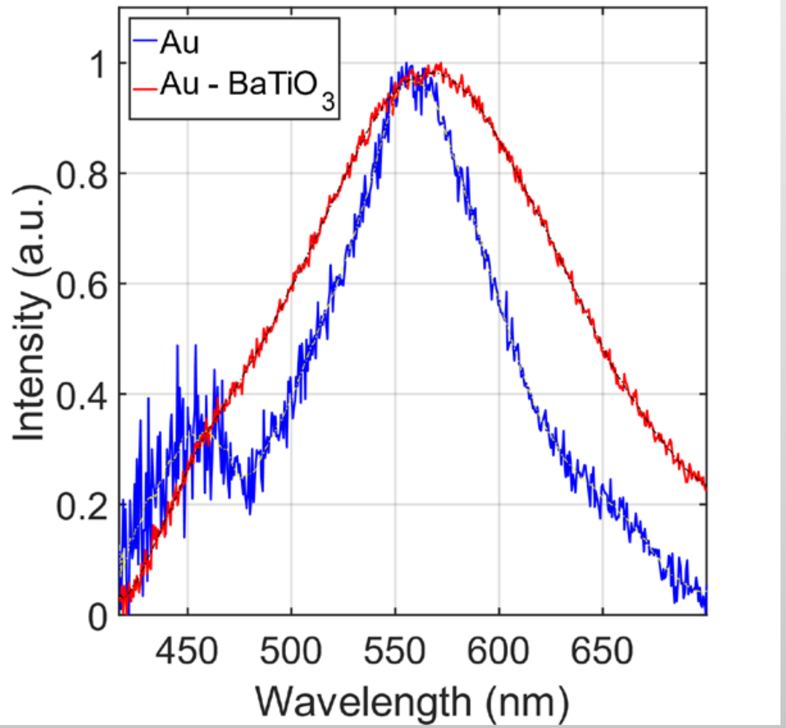


Both 100 nm Ø

Collaboration with Lucio Isa (ETH) and Heiko Wolf (IBM)



Extinction



SHG enhancement : 5-15

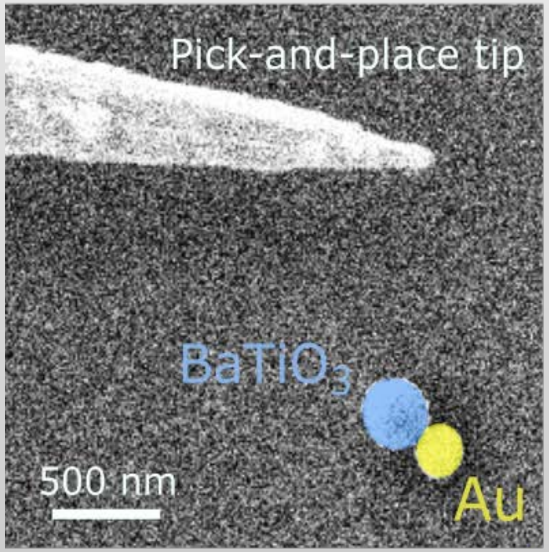
Timpu, F.; Hendricks, N. R.; Petrov, M.; Ni, S.; Renaut, C.; Wolf, H.; Isa, L.; Kivshar, Y.; Grange, R. **Nano Letters**, 17, 5381, 2017.

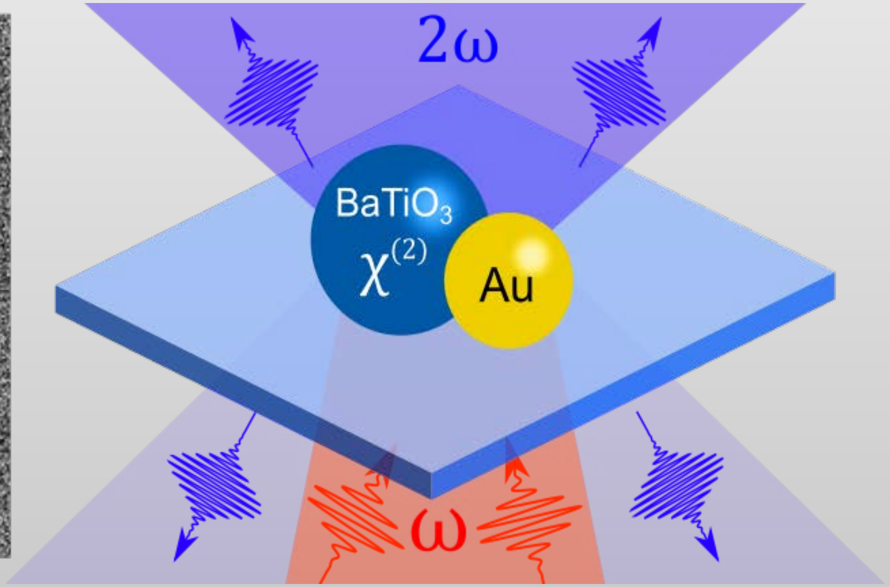
High-throughput and **reduced fabrication complexity**

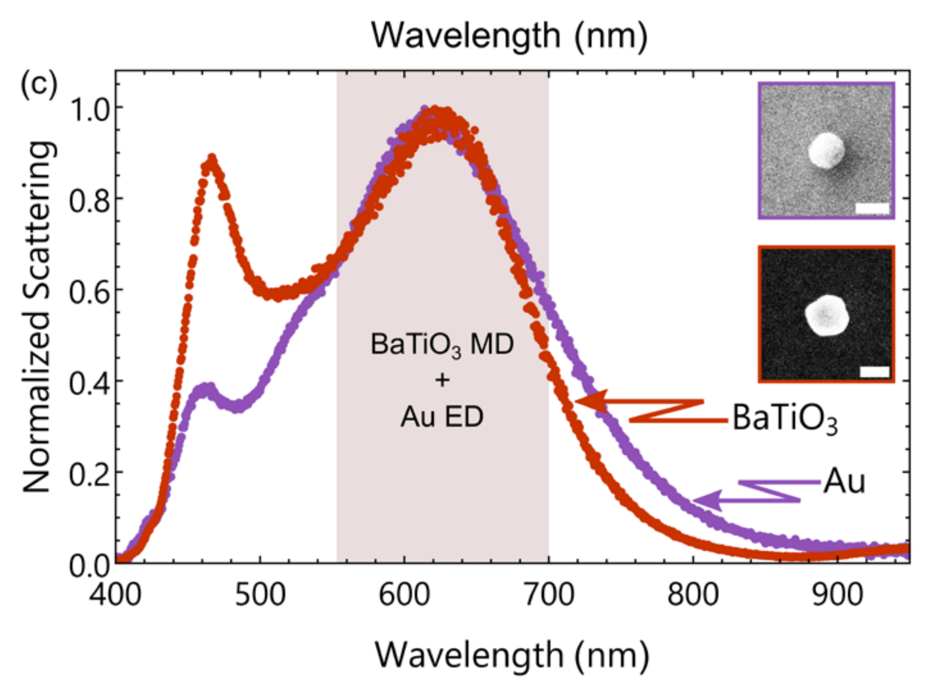
Combination of plasmonics with $\chi^{(2)}$ materials

Reshaping the Second-Order Polar Response

Hybrid Nanodimers







Renaut et al., **Nano Letters**, just accepted, 2019

Combination of plasmonics with $\chi^{(2)}$ materials

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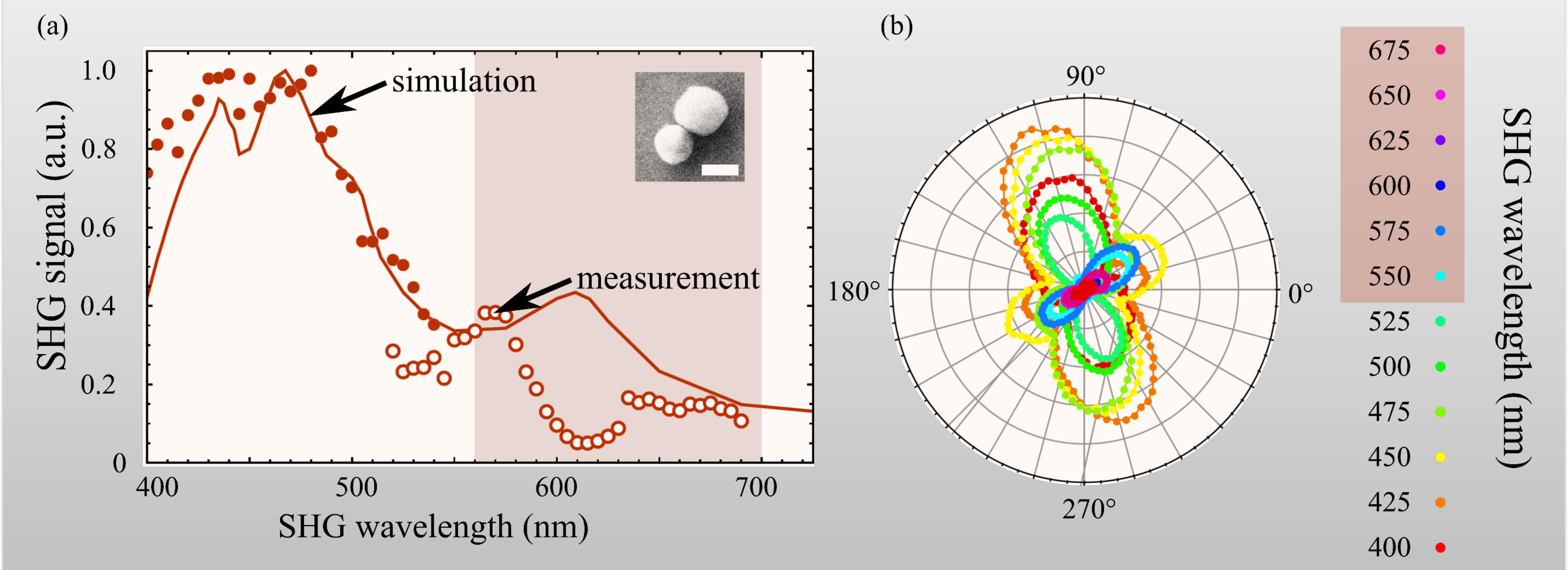


Renaut et al., **Nano Letters**, just accepted, 2019

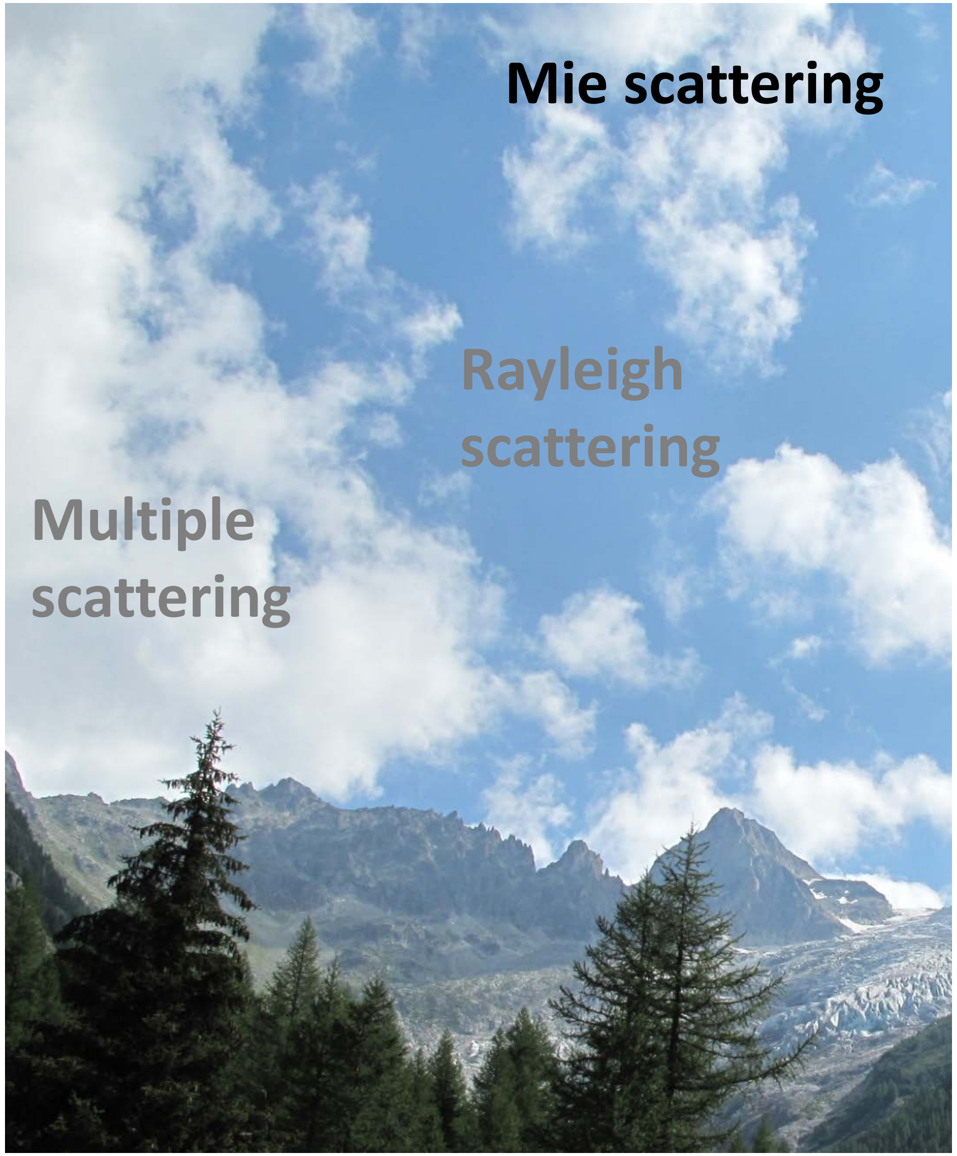
Drawback of metals : thermal losses

J. B. Khurgin, How to deal with loss in plasmonics and metamaterials, Nature Nanotechnology, 10, 2015.

Strategies to enhance nonlinear optical signals

- with plasmonics
- **with the $\chi^{(2)}$ material itself**

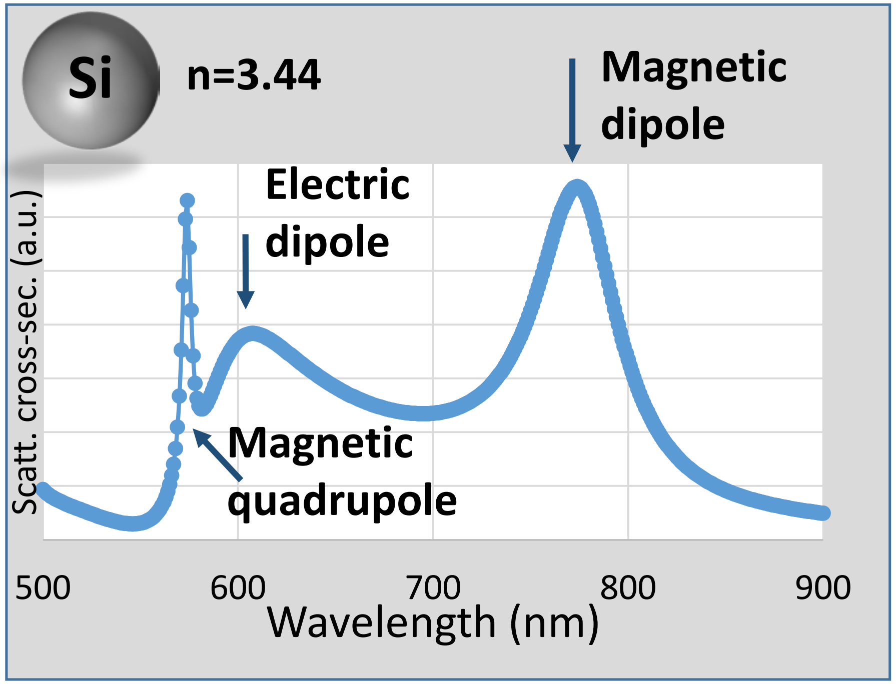
Mie resonances of the $\chi^{(2)}$ material istelf



Mie resonances in material with n > 2 and size ~λ :

electric and magnetic resonance have comparable strength

Silicon nanopartices with 200 nm



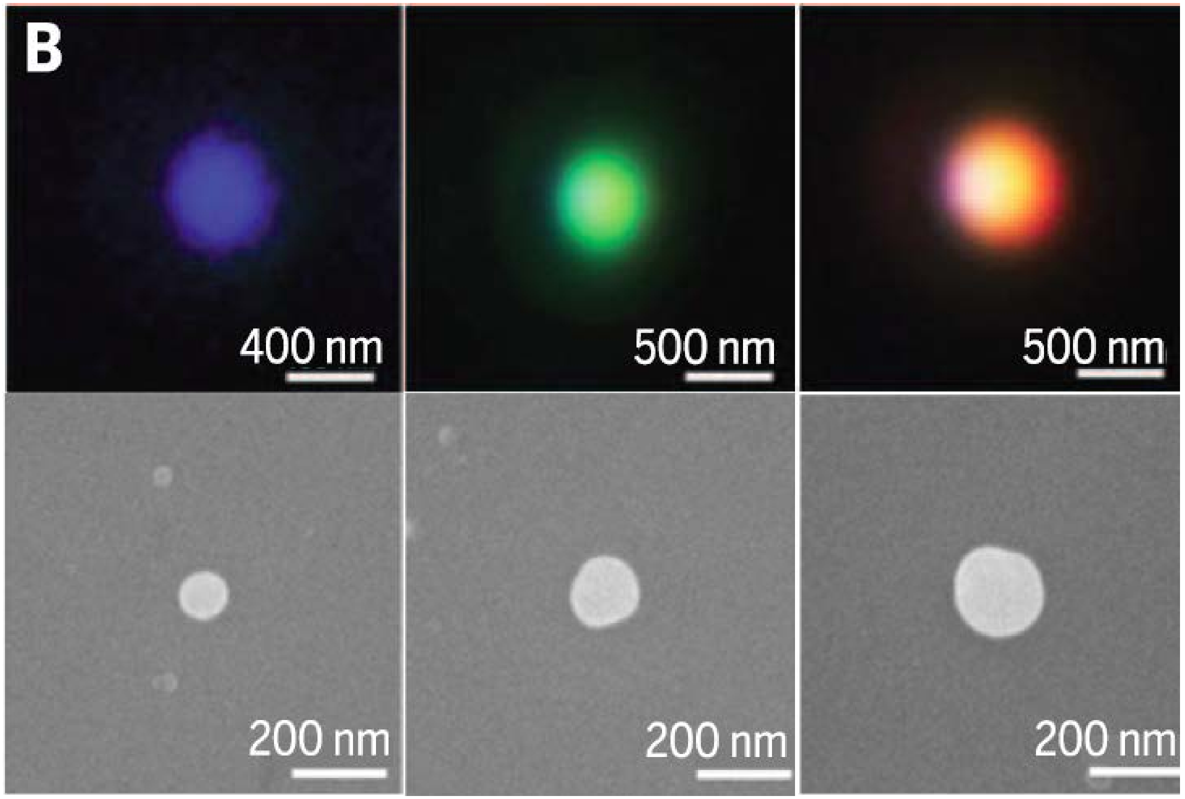
- A. García-Etxarri et al., *Opt. Express*, 19, (2011)
- Krasnok, A. et al., Opt. Express 20, 20599 (2012)
- A. B. Evlyukhin et al. , Nano Lett. 12,3749, (2012)
- Zywietz, U. et al. Nat. Commun. 5:3402 (2014)

Mie resonances of the $\chi^{(2)}$ material istelf

Mie resonances in material with n > 2 and size ~λ :

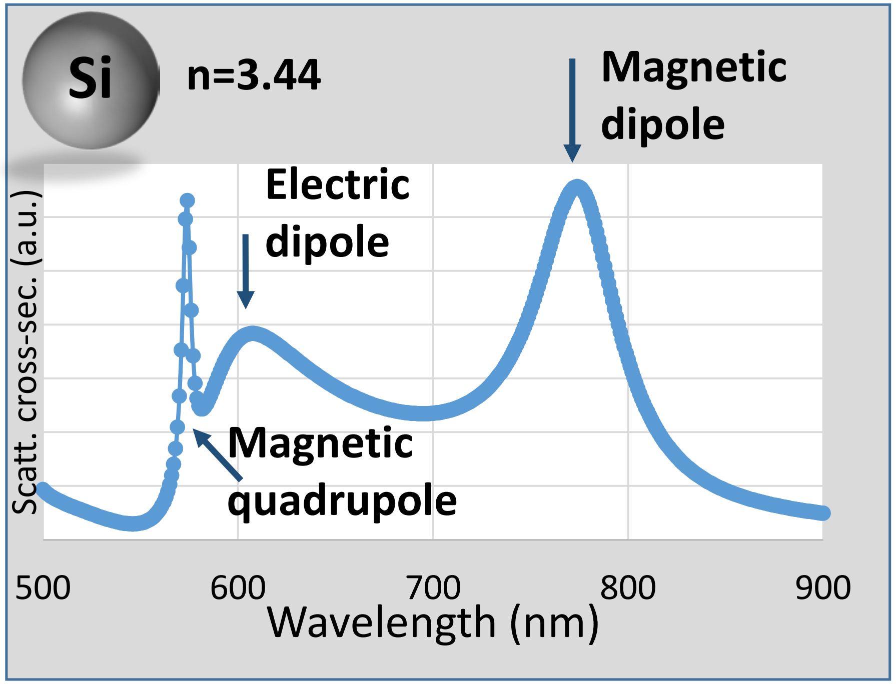
electric and magnetic resonance have comparable strength

Colors vary with sizes of the particle



Arseniy I. Kuznetsov et al. Science 2016, 354, 2472

Silicon nanopartices with 200 nm



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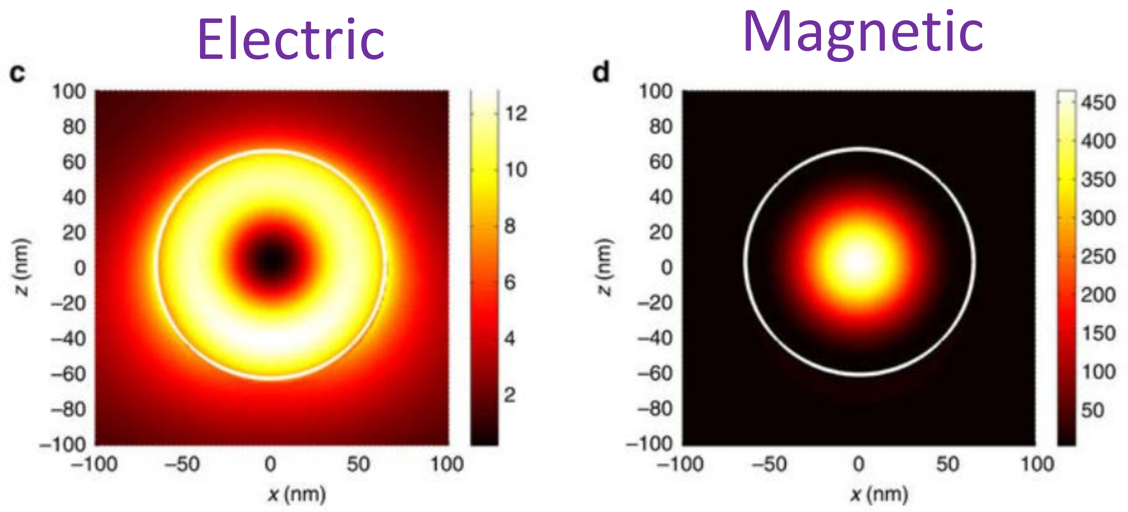
Calculated field intensities at the **magnetic dipole resonances**



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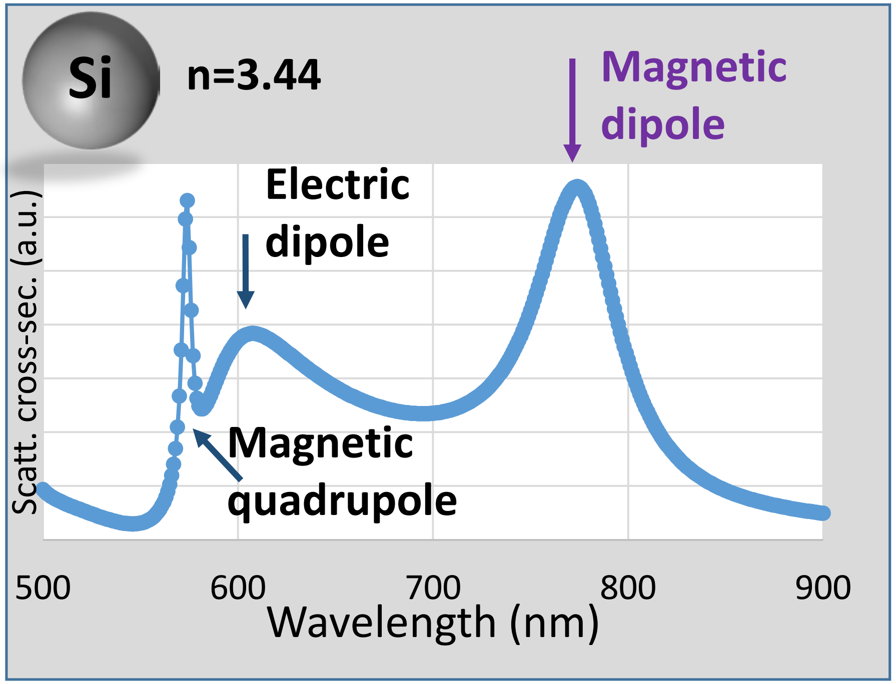

'Dielectric' material: electromagnetic field amplified in the volume of the nanoparticle

- A. García-Etxarri et al., *Opt. Express*, 19, (2011)
- Krasnok, A. et al., Opt. Express 20, 20599 (2012)
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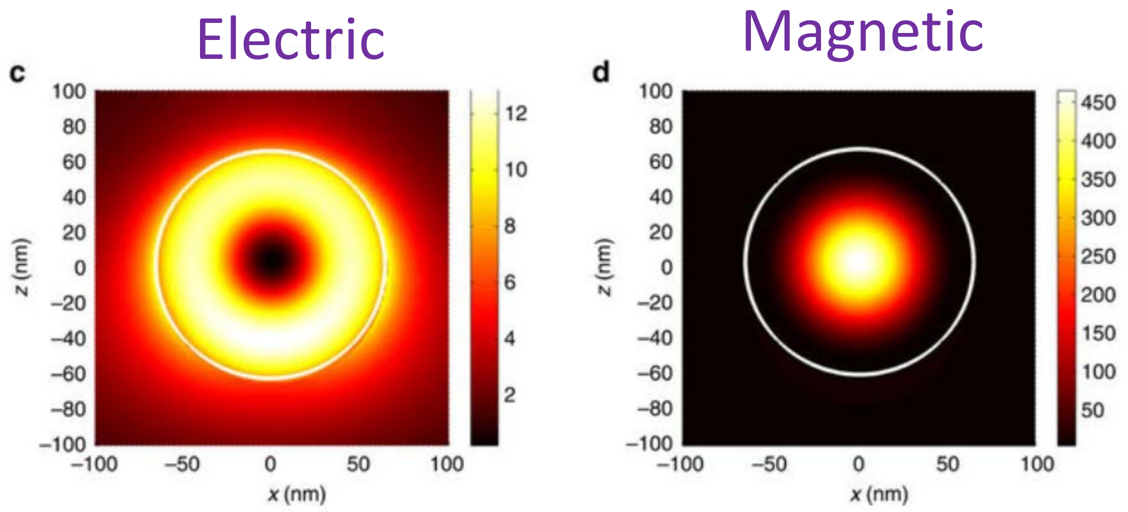
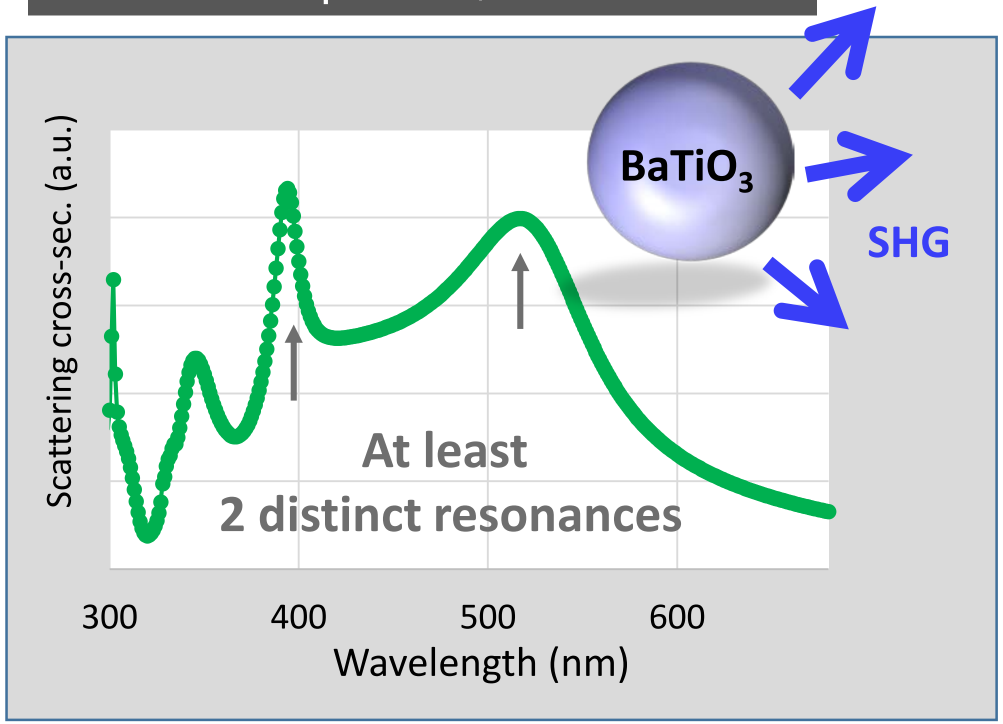


'Dielectric' material: electromagnetic field amplified in the volume of the nanoparticle

Material	$\chi^{(2)}$ coeff. (pm/V)
Silicon	0
SiO_2 (Quartz)	0.335
$BaTiO_3$	6.8 to 17
$LiNbO_3$	6 to 34
GaAs	134 to 256

Mie resonances of the $\chi^{(2)}$ material istelf

BaTiO3 nanoparticle, d = 200 nm



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F. Timpu, A. Sergeyev, N. Hendricks, and R. Grange, ACS Photonics, 4, 2017.

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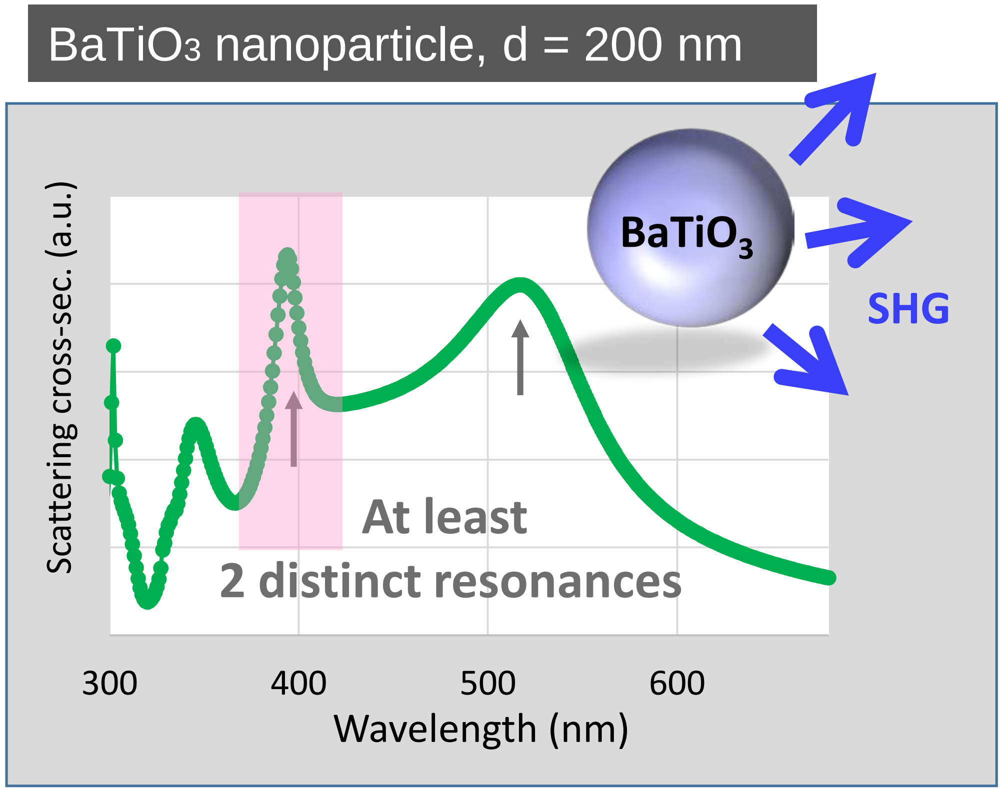
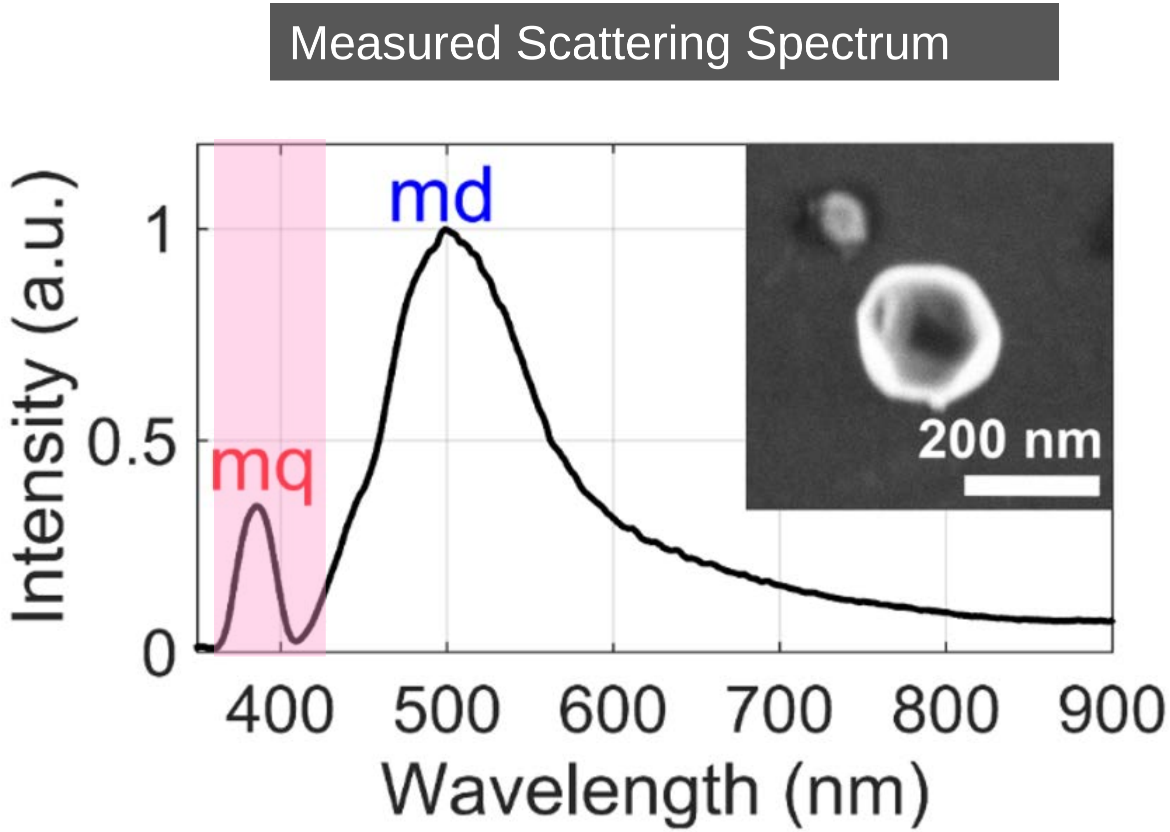
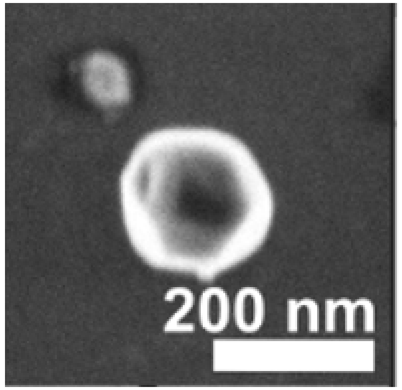
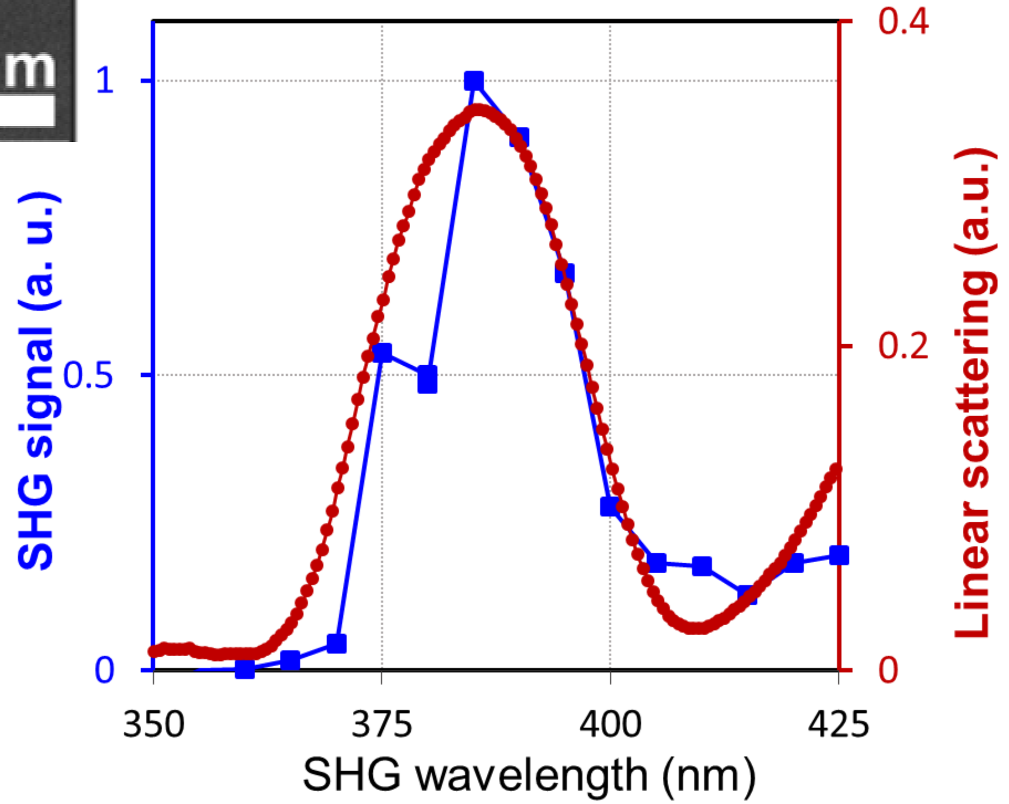


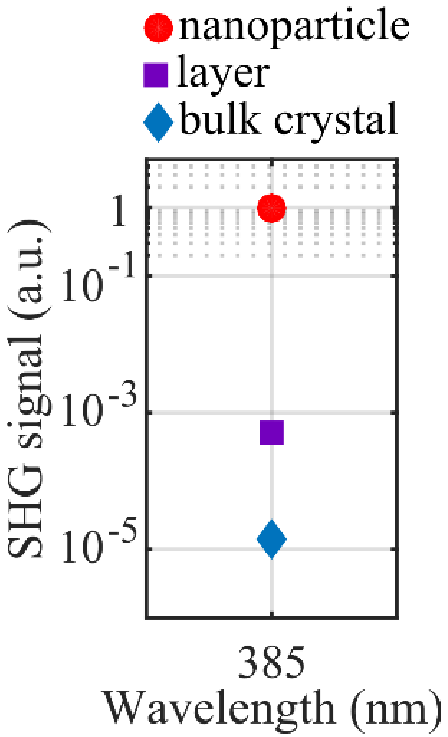


F. Timpu, A. Sergeyev, N. Hendricks, and R. Grange, ACS Photonics, 4, 2017.

Mie resonances enhance SHG from single nanoparticle







10^4 enhancement with a single resonance !

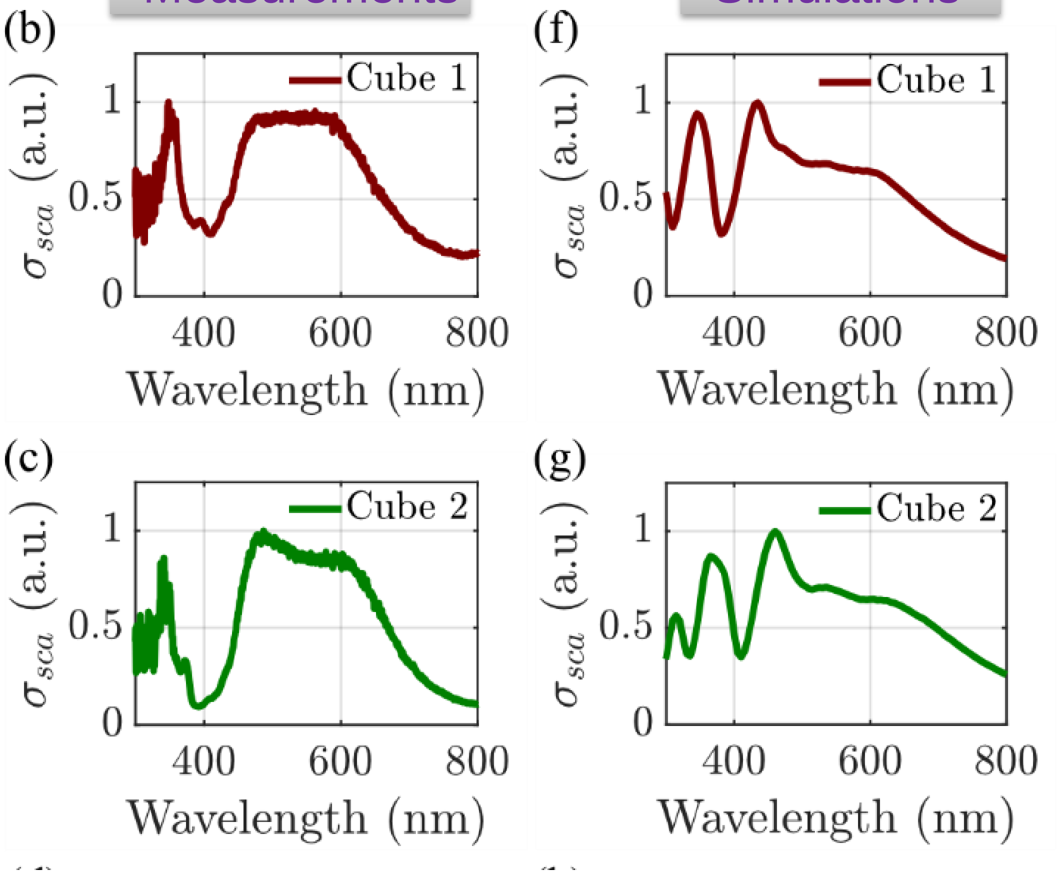
F. Timpu, A. Sergeyev, N. Hendricks, and R. Grange, ACS Photonics, 4, 2017.

Mie resonances in Lithium Niobate Nanocubes

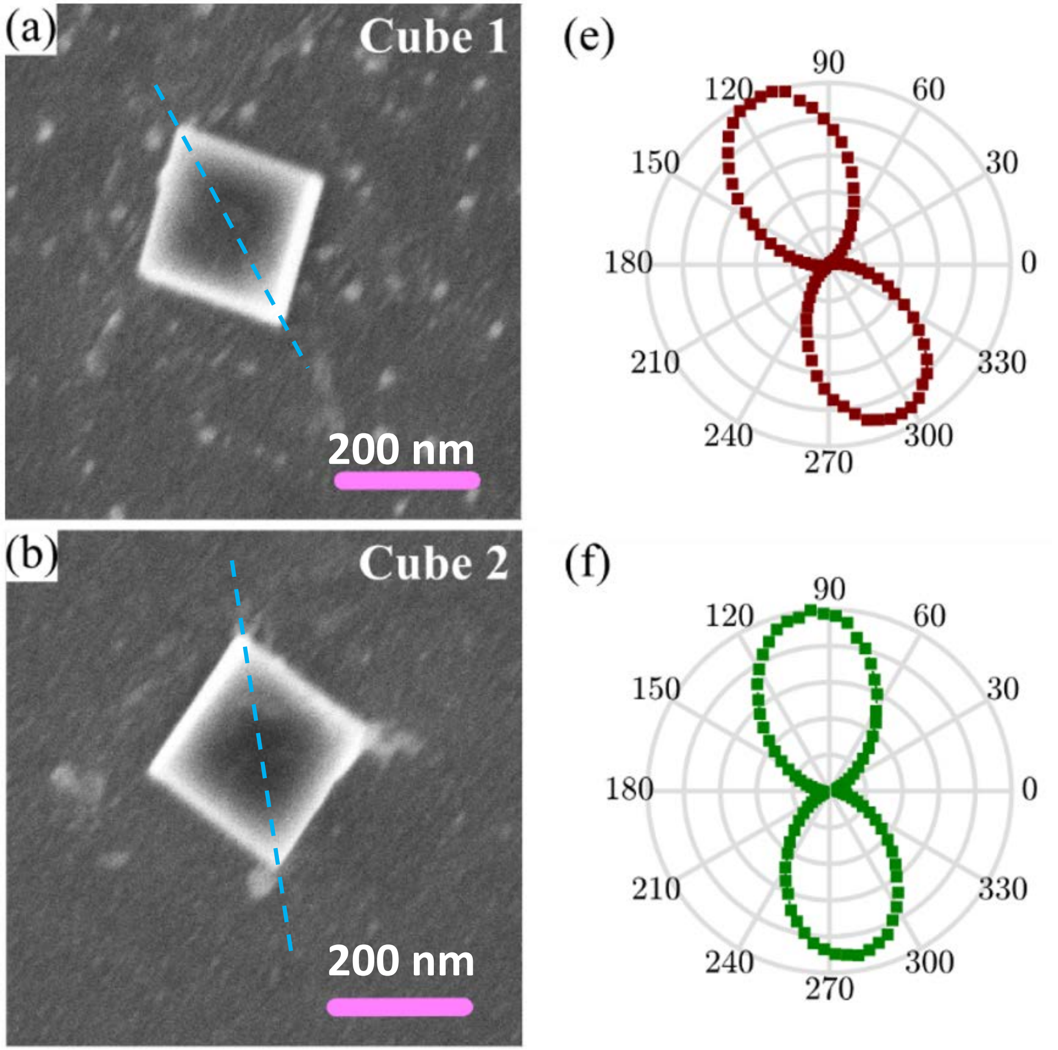
Linear scattering

Measurements

Simulations



SHG Polar response



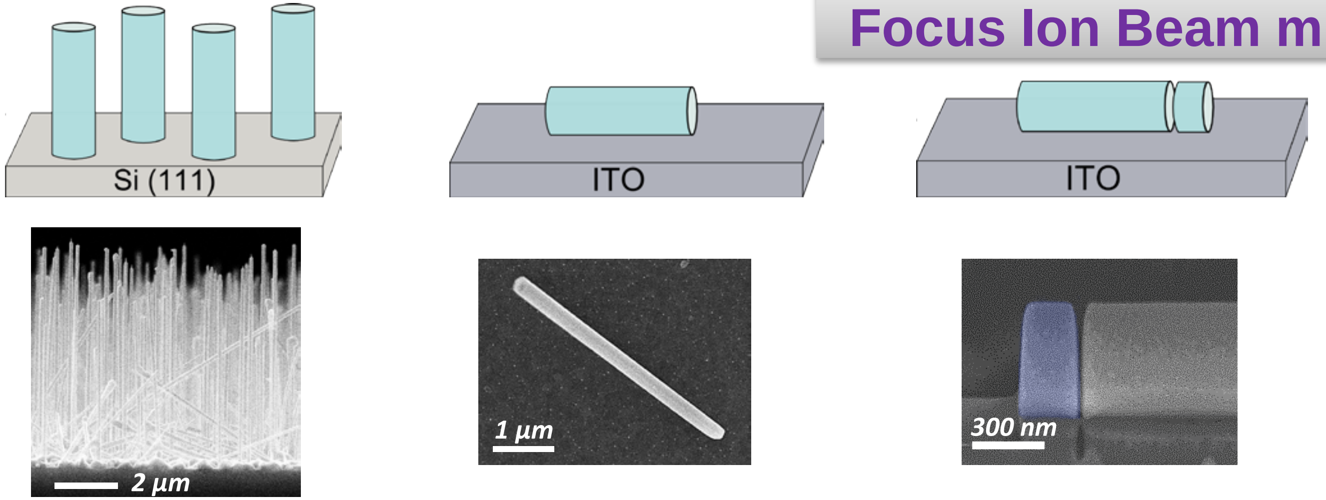
F. Timpu, et al, under review 2019

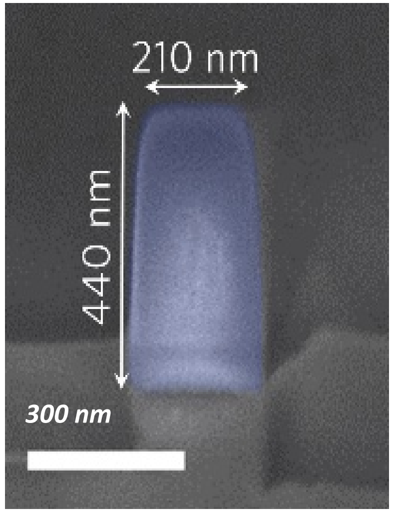
Mie resonances in III-V nanowires

Anapoles in Free-Standing III-V Nanodisks

$Al_{0.3}Ga_{0.7}As$ nanowires grown on Si

Focus Ion Beam milling

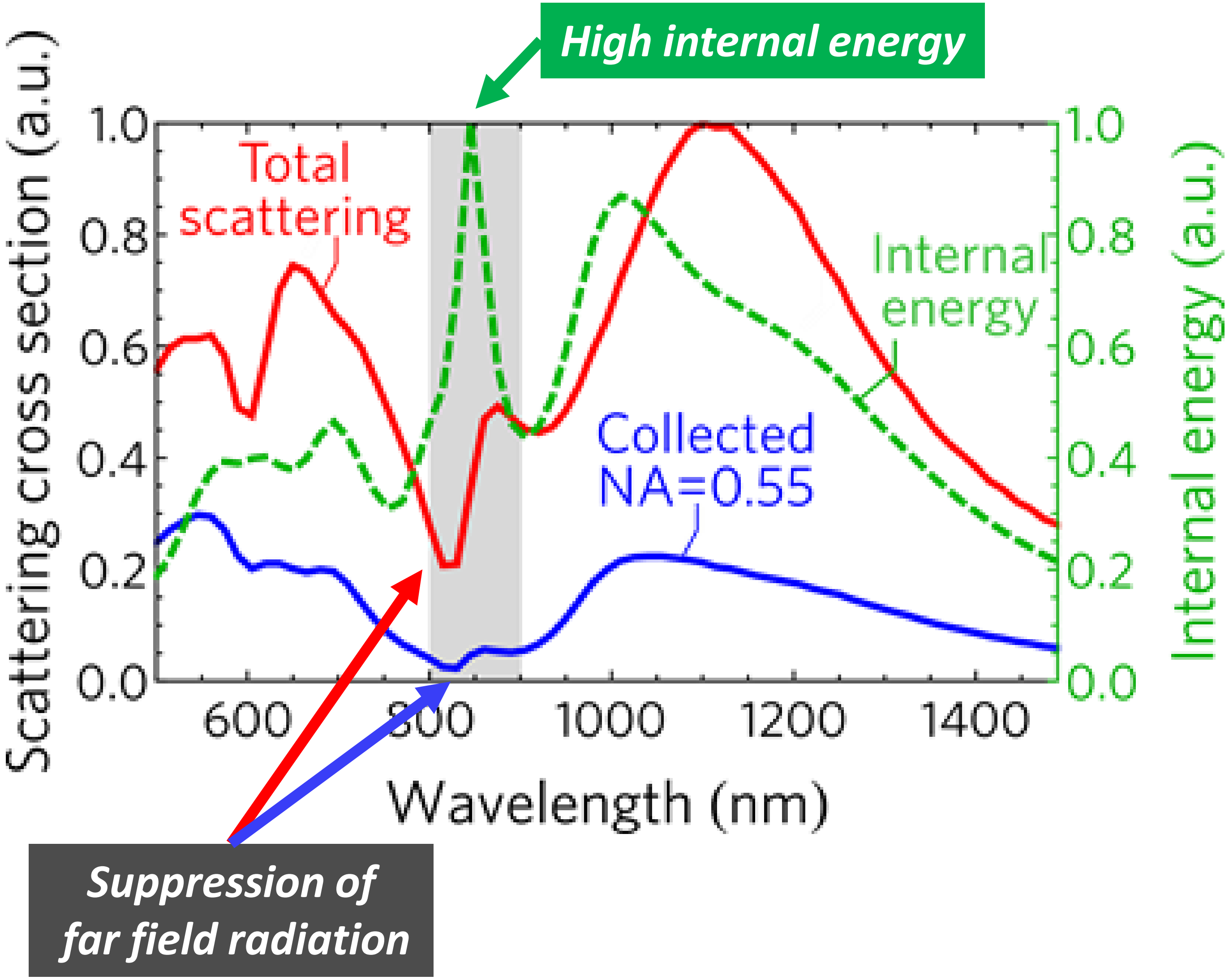


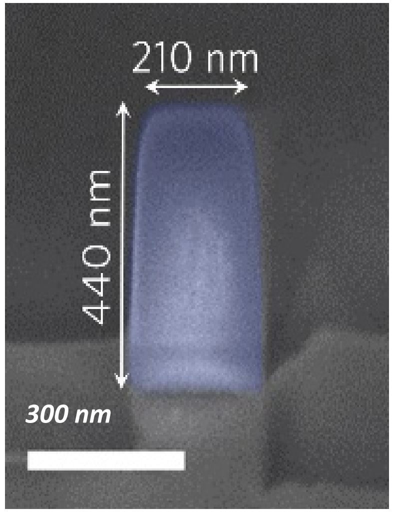


M. Timofeeva,…, R. Grange, Nano Letters, 18,6, 2018

Mie resonances in III-V nanowires

Anapoles in Free-Standing III-V Nanodisks

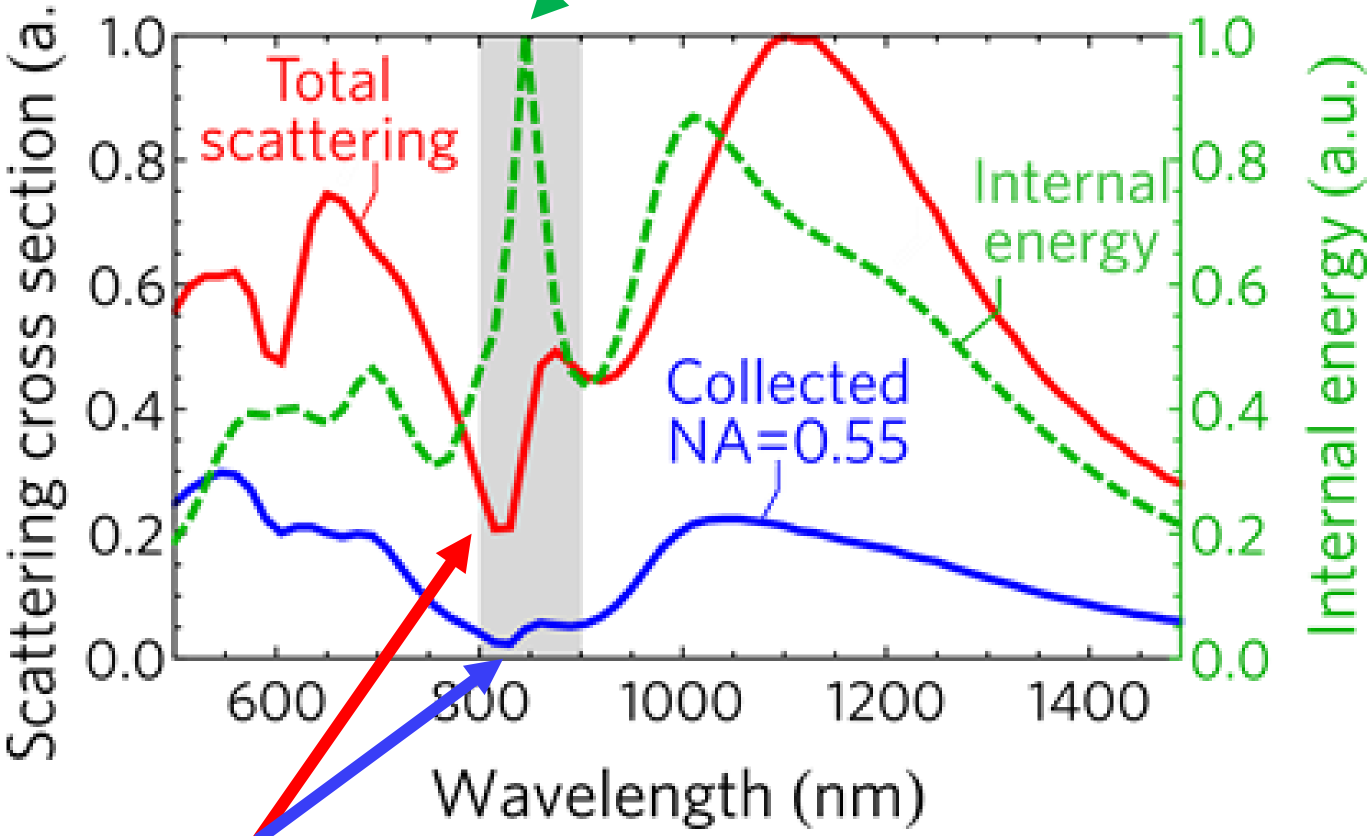




M. Timofeeva,..., R. Grange, Nano Letters, 18,6, 2018

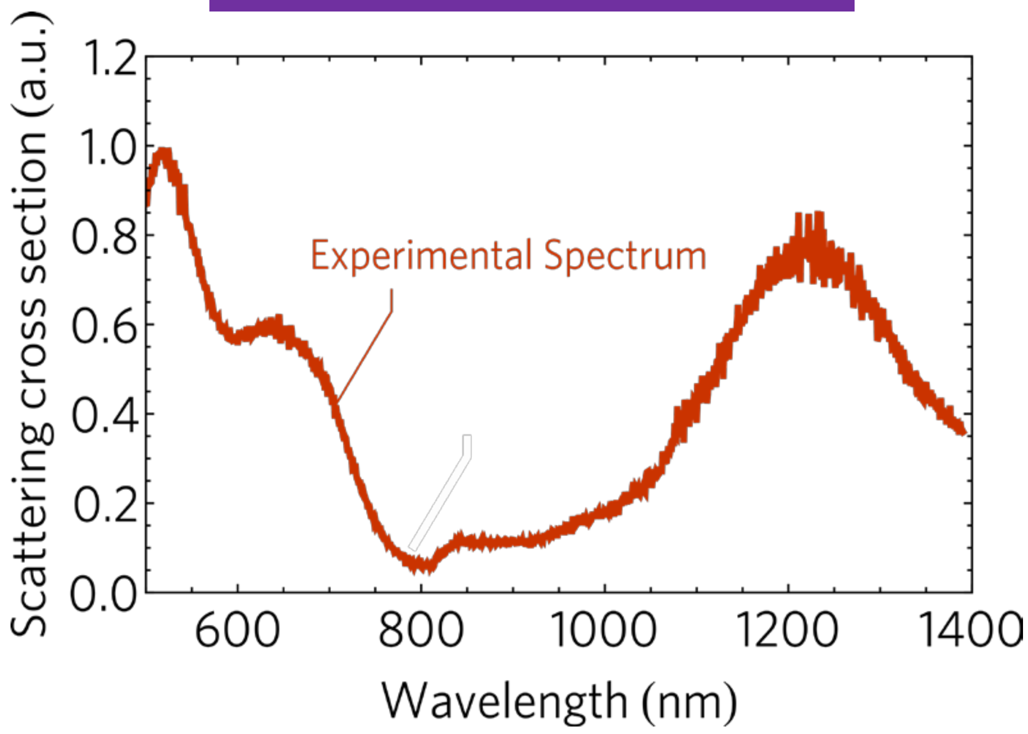
Anapoles in Free-Standing III-V Nanodisks

High internal energy



Suppression of far field radiation

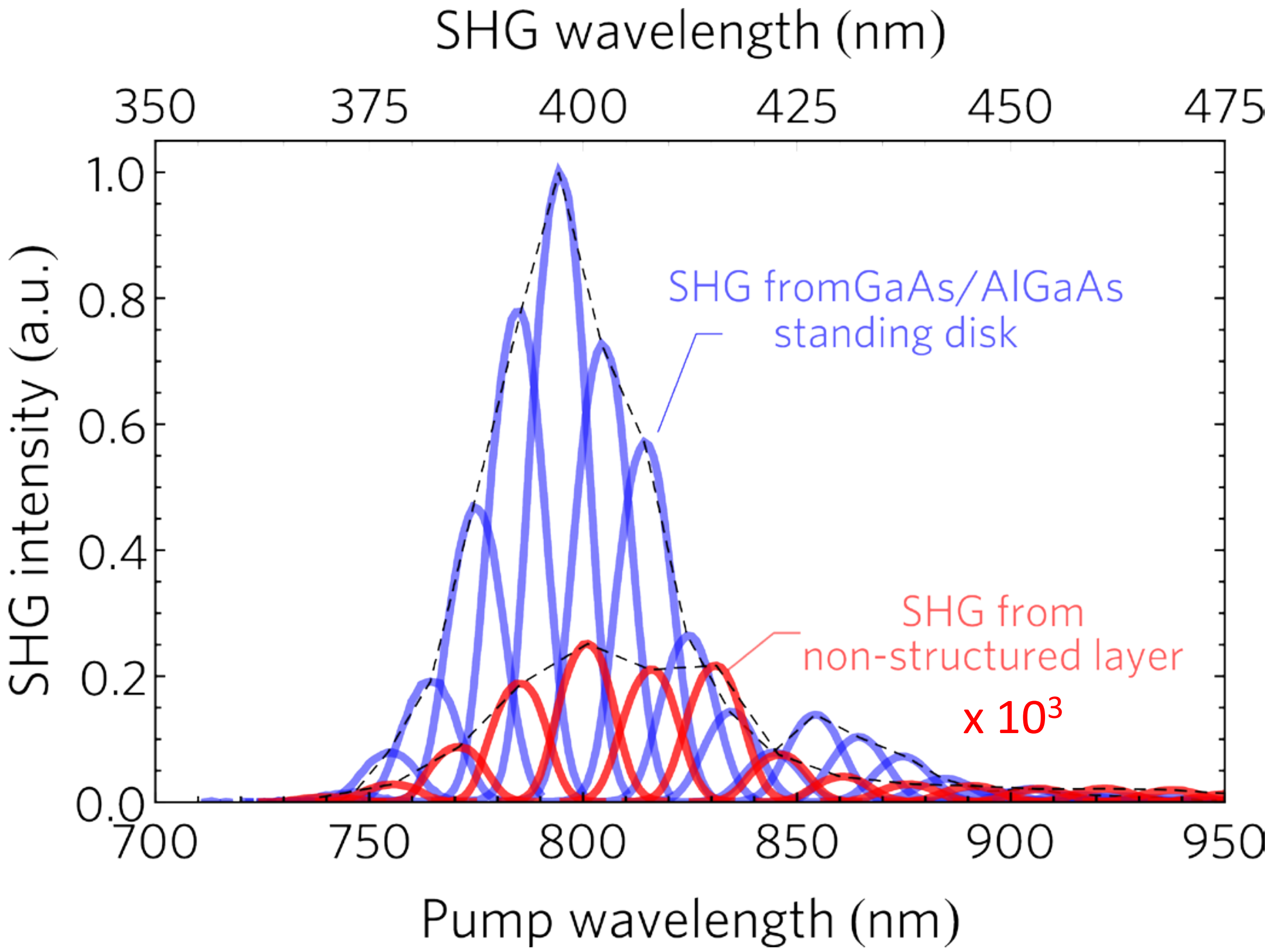
Linear Measurement

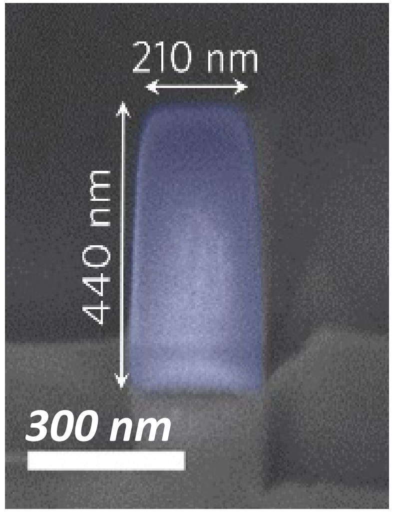


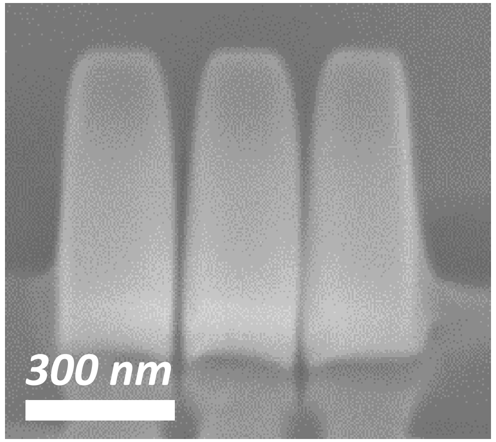
M. Timofeeva,..., R. Grange, Nano Letters, 18,6, 2018

Anapoles in Free-Standing III-V Nanodisks

Nonlinear Measurements







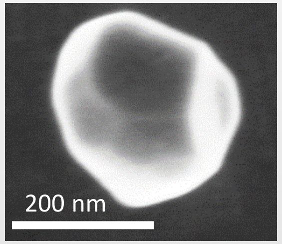
Strong nonlinear response:

>10^3 SHG enhancement

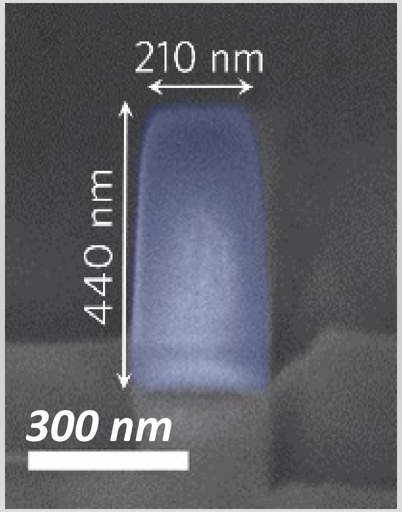
M. Timofeeva,…, R. Grange, Nano Letters, 18,6, 2018

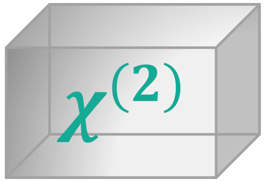
$\chi^{(2)}$ materials at small scale

$\chi^{(2)}$ Building blocks



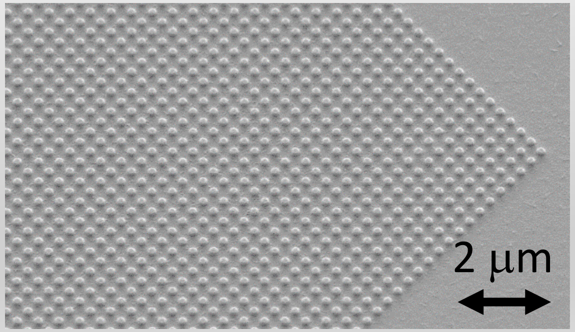
20 - 100s nm





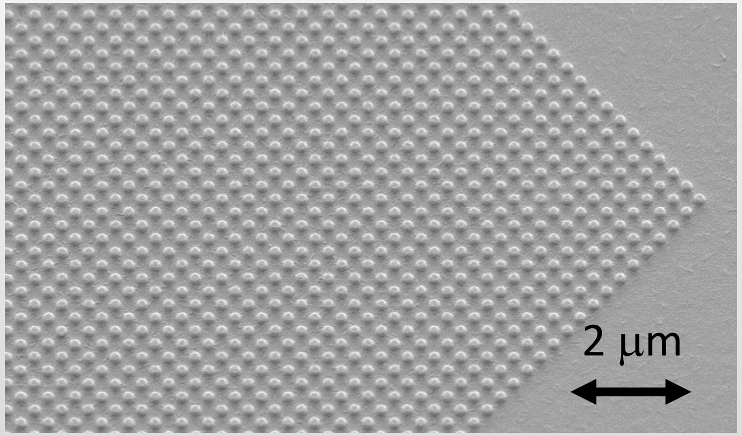
Top-down fabrication

Flat photonic structures



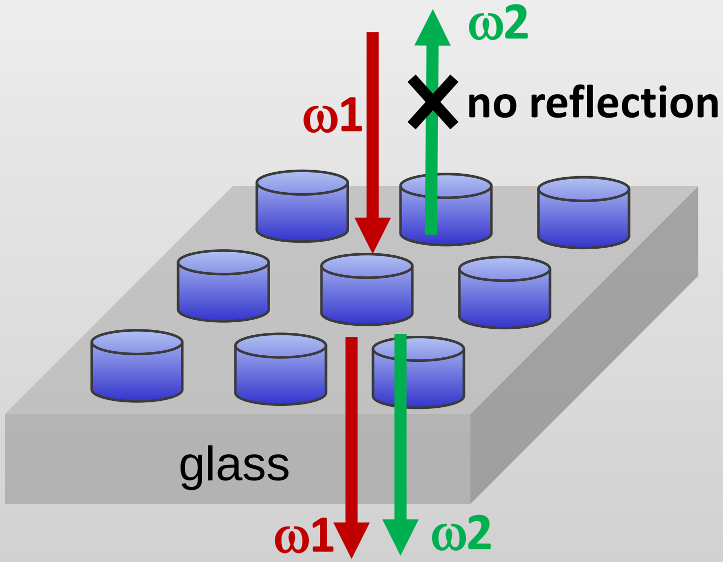
Perspective: Flat Nonlinear Photonic Devices

$BaTiO_3$ thin film for nonlinear metasurfaces



Pulse Laser Deposition of M. Trassin and M. Fiebig, Material sciences, ETHZ

Artificial nanostructured materials with exotic electromagnetic responses



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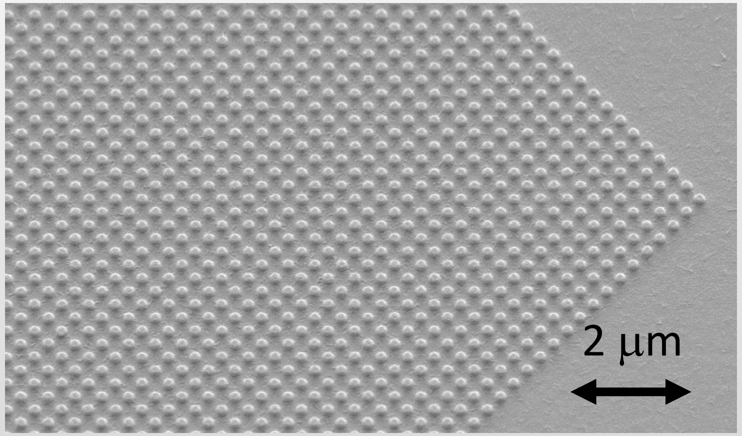
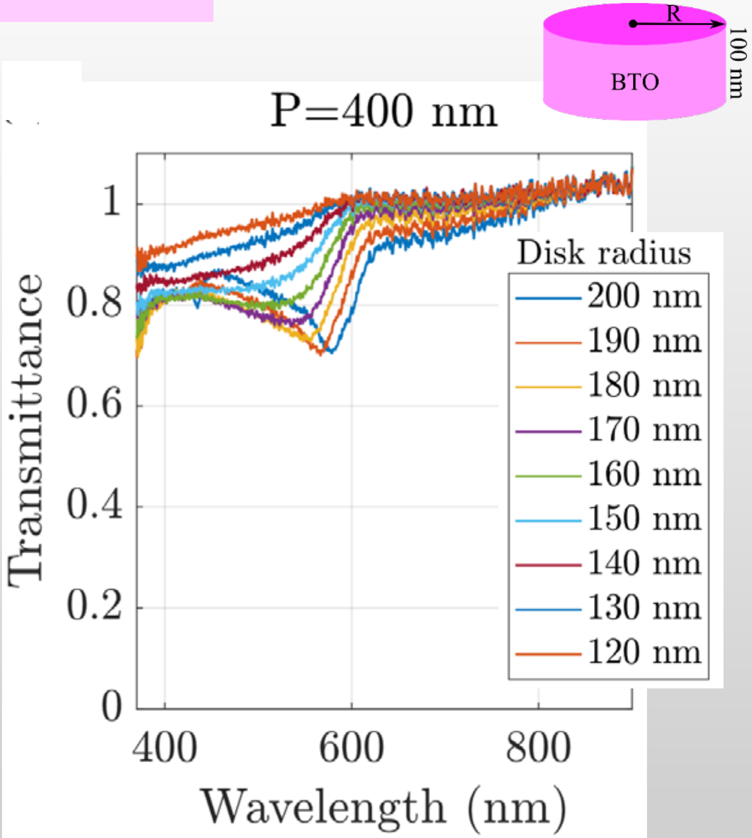
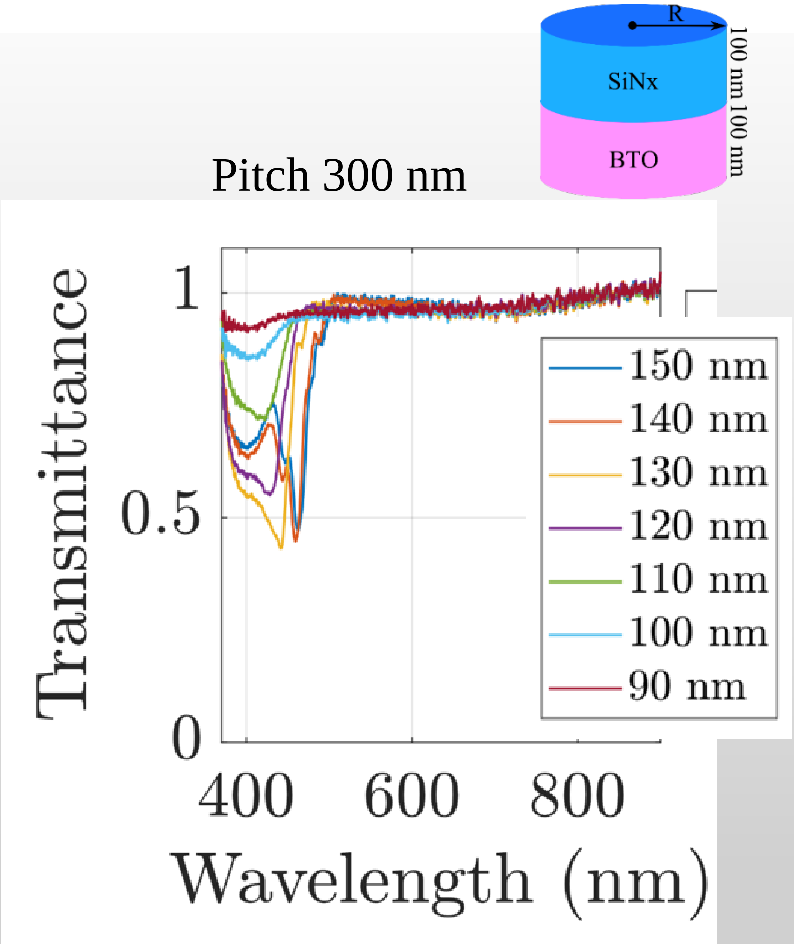


Pulse Laser Deposition of M. Trassin and M. Fiebig, Material sciences, ETHZ

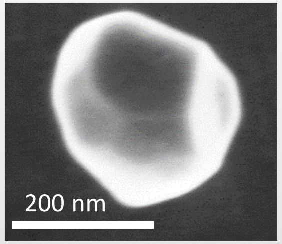




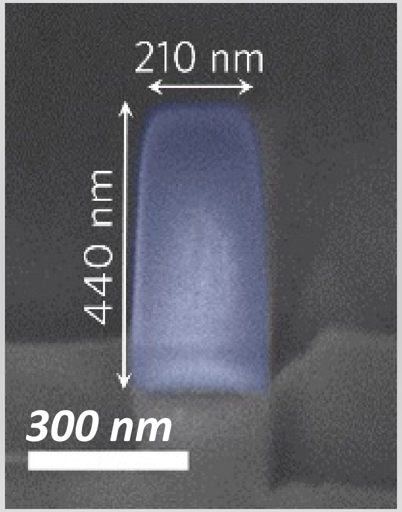
Fabrication and etching challenges of oxides thin films

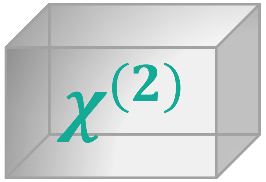
$\chi^{(2)}$ materials at small scale

$\chi^{(2)}$ Building blocks



20 - 100s nm

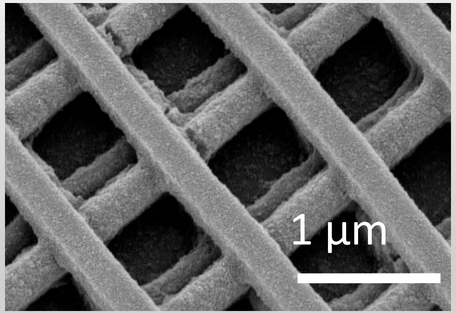




mm - cm

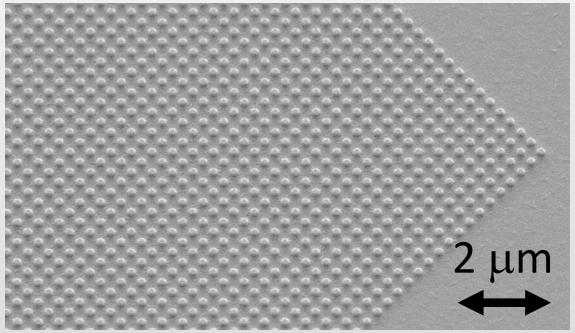
Bottom-up processing

Wide surface area photonic crystal



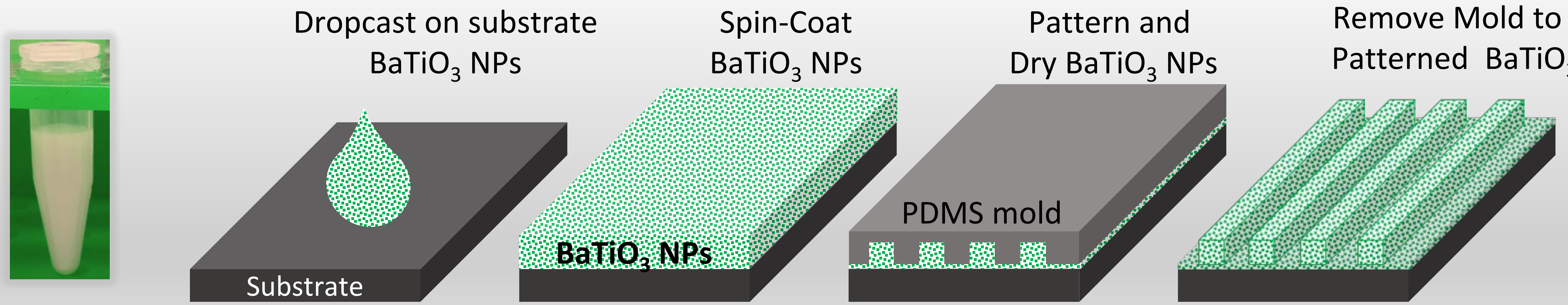
Top-down fabrication

Flat photonic structures

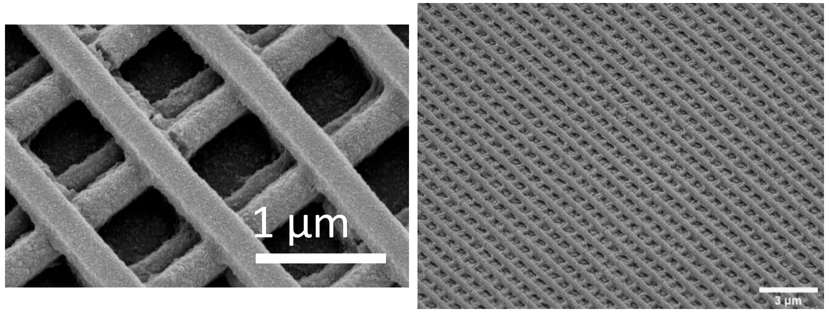


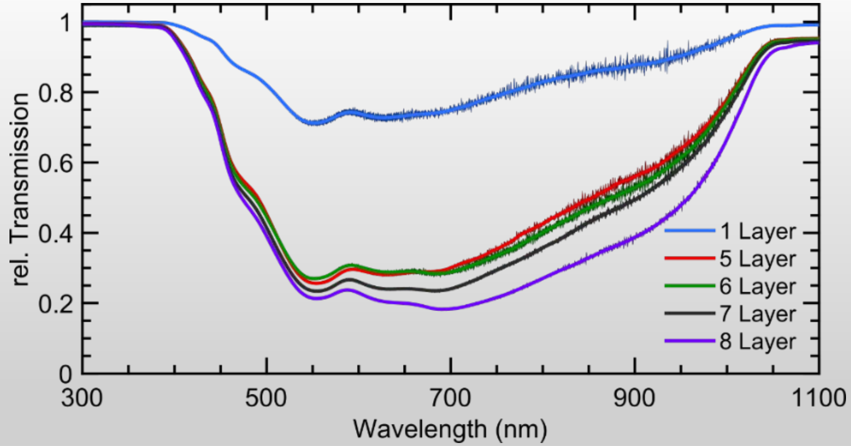
Bottom-up assembly for large surface area

Colloidal Solution Processing and nanoimprint lithography



Woodpile up to 8 layers

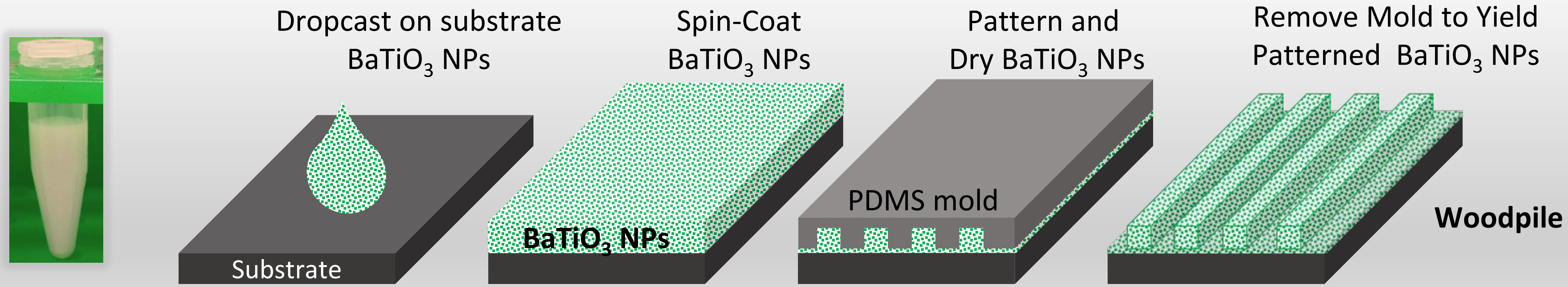




V. V. Vogler-Neuling, … and R. Grange, Metamaterials Marseille, France 08.28-31, Talk (2017).

Bottom-up assembly for large surface area

Colloidal Solution Processing and nanoimprint lithography



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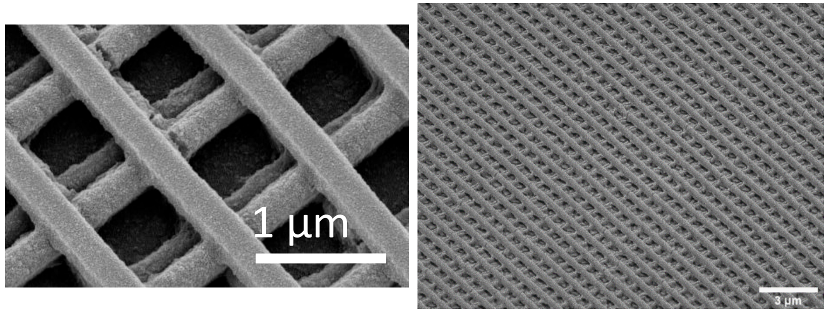
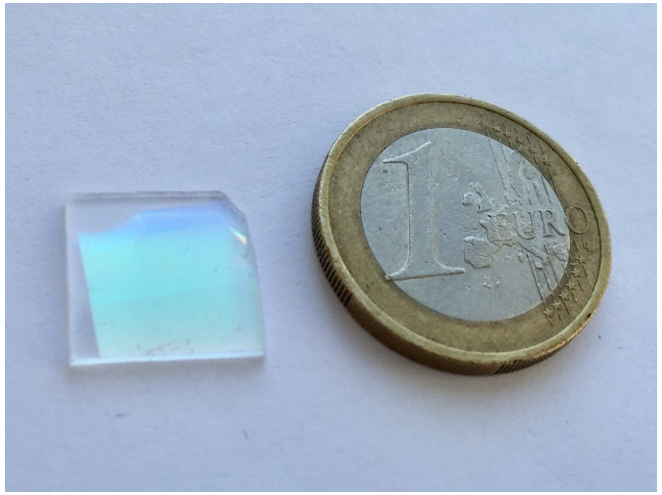




Large surface area 2 x 2 cm

Disposable sensors

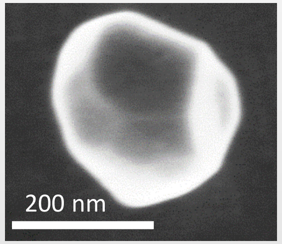
No etching

V. V. Vogler-Neuling, … and R. Grange, Metamaterials Marseille, France 08.28-31, Talk (2017).

$\chi^{(2)}$ materials at small scale

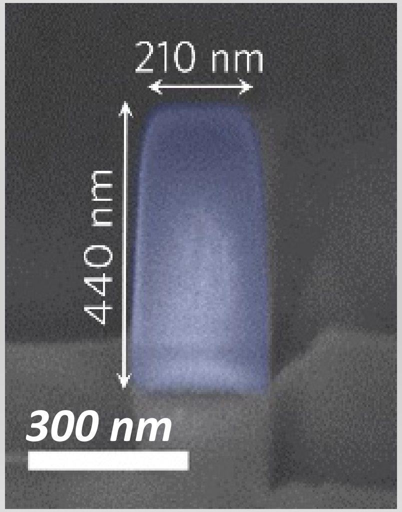
$\chi^{(2)}$ Building blocks

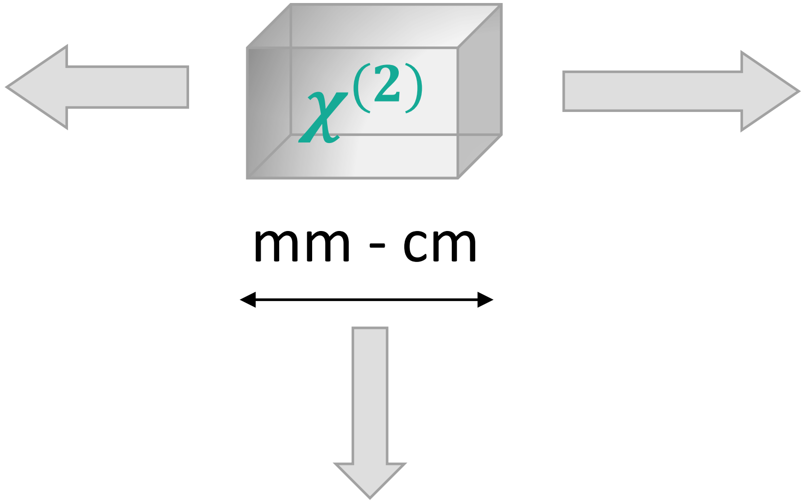
BaTiO$_3$



20 - 100s nm

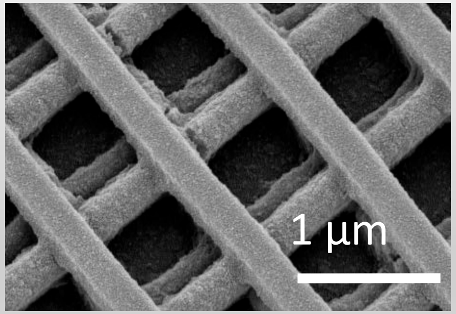
AlGaAs anapole





Bottom-up processing

Wide surface area photonic crystal



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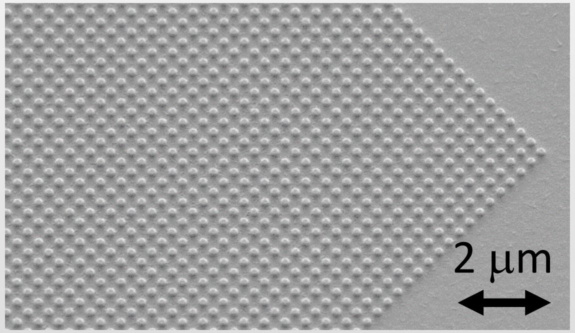
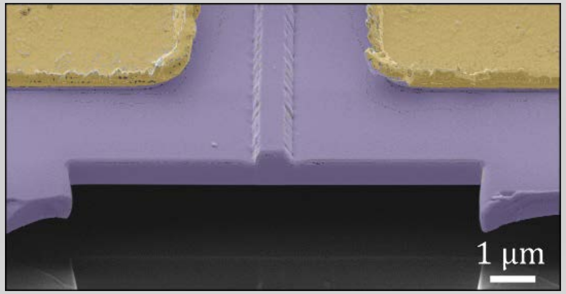
Flat photonic structures

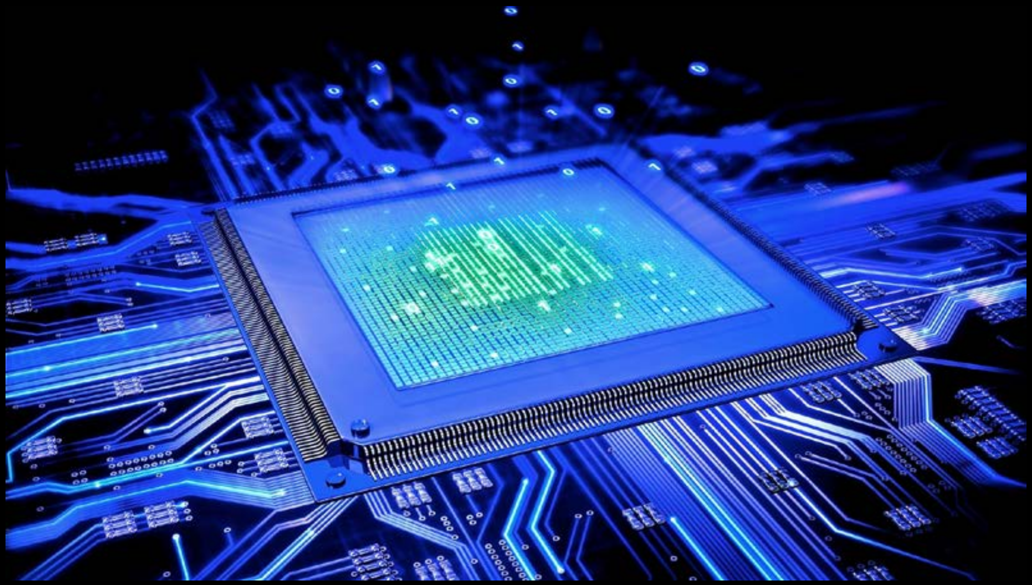


Integrated devices



Integrated Photonics

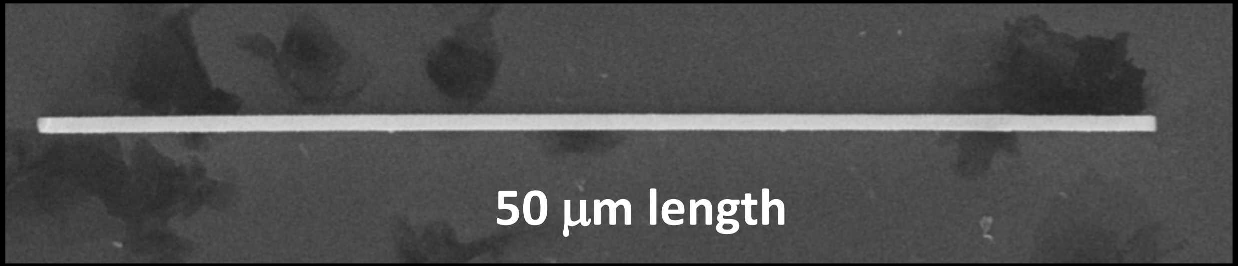
Less weight and more transmitted data



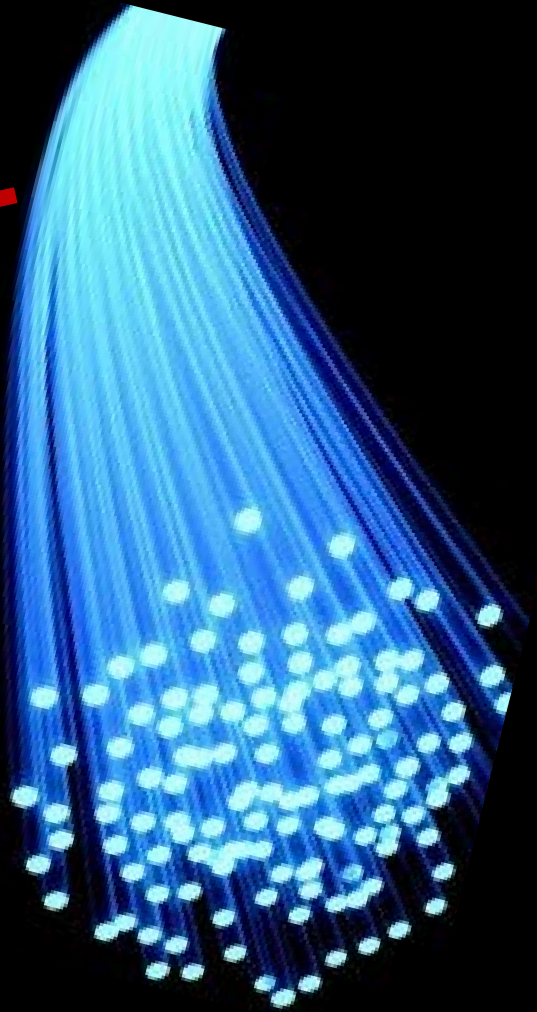
Broadly transparent, low losses, fast, compact, robust

LiNbO$_3$ nanowaveguides by ion beam enhanced etching

400 nm diameter



100 x



A. Sergeyev,... R. Grange, Opt. Exp. **21**, 19012, 2013.

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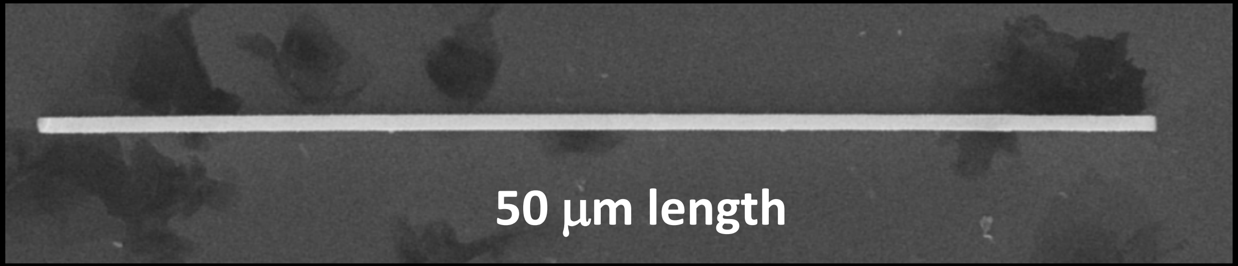
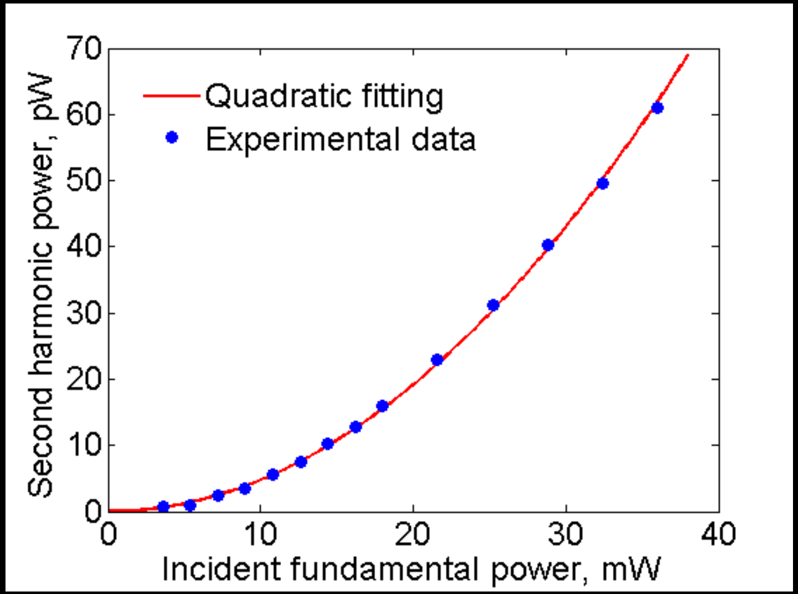


Signal dependence on the incident laser power



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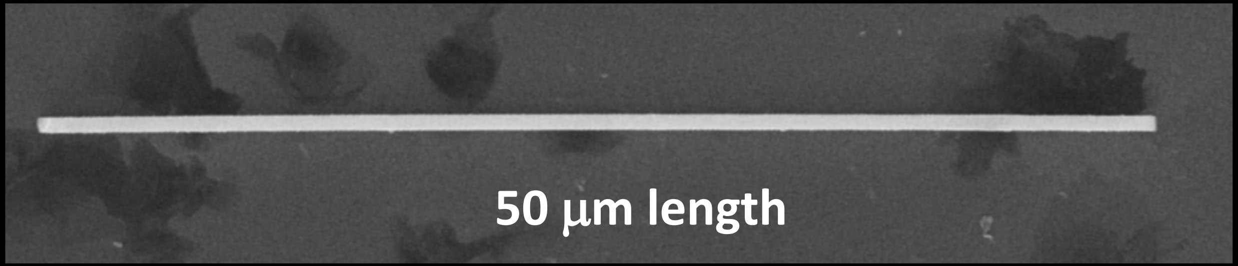


How to achieve phase-matching?

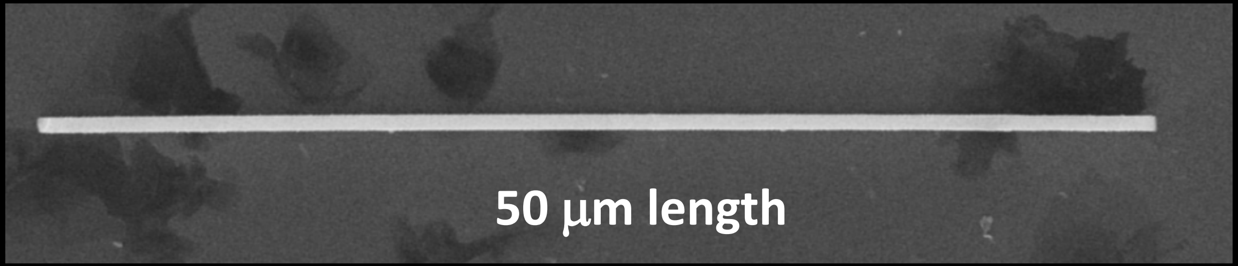
In waveguides

modal phase-matching

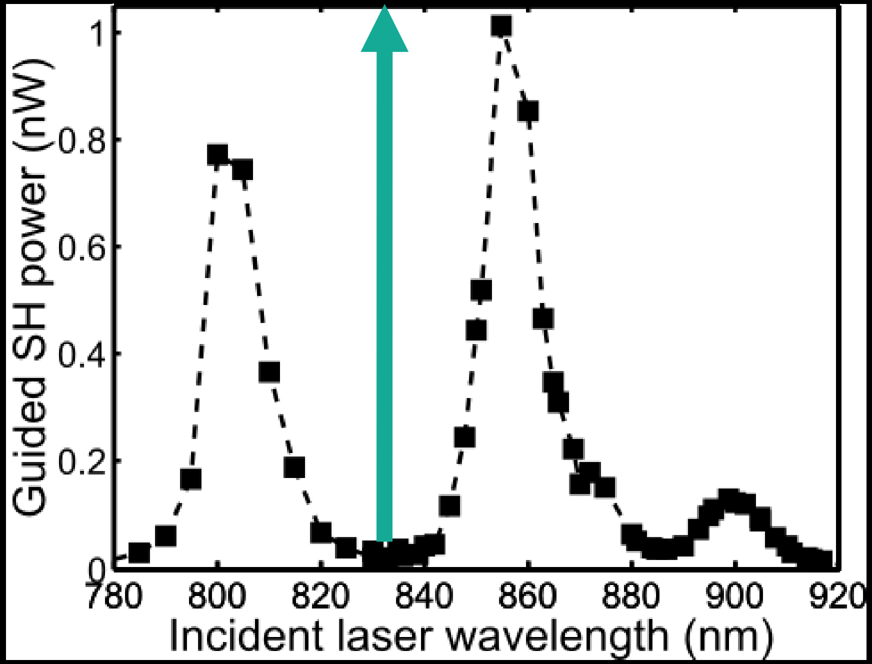
Sergeyev, A.; et al. ACS Photonics 2015, 2 (6), 687–691.

LiNbO$_3$ nanowaveguides by ion beam enhanced etching

400 nm diameter



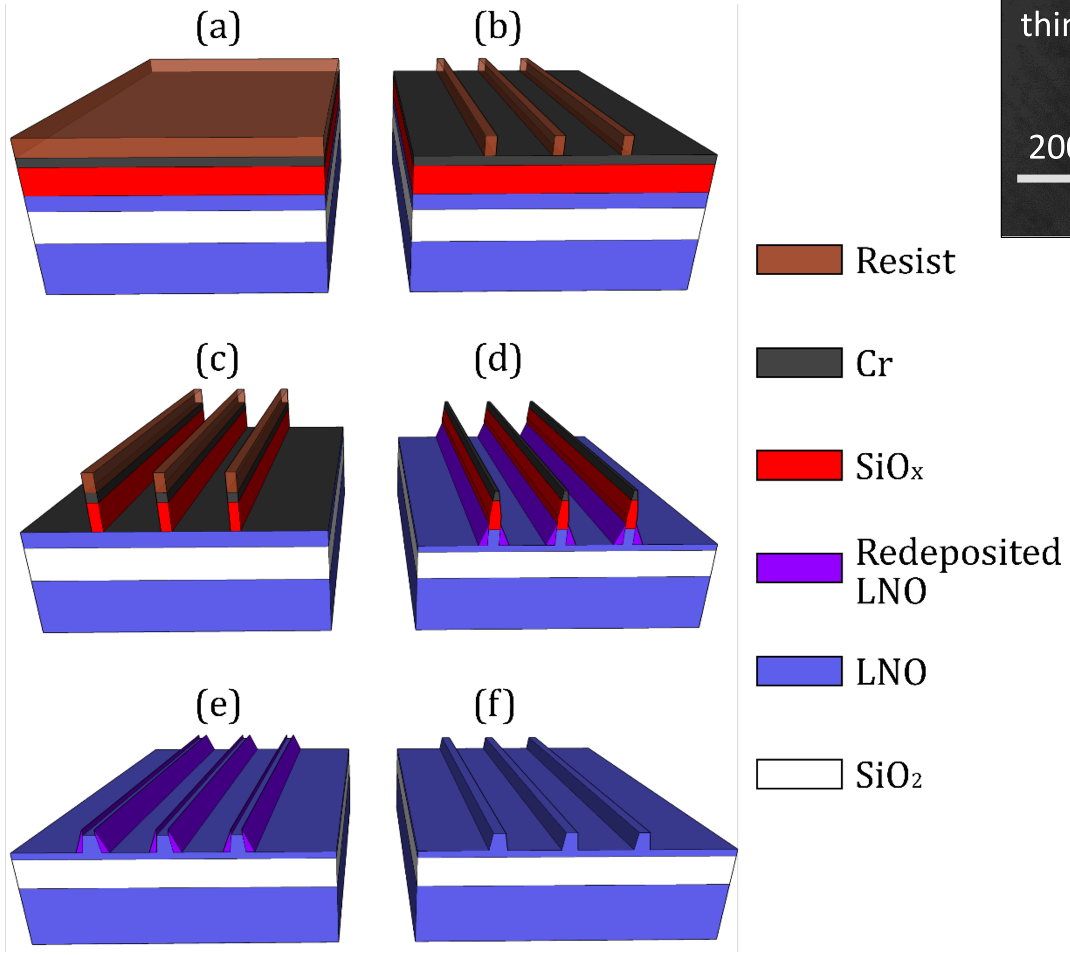
50 times increase with modal phase matching

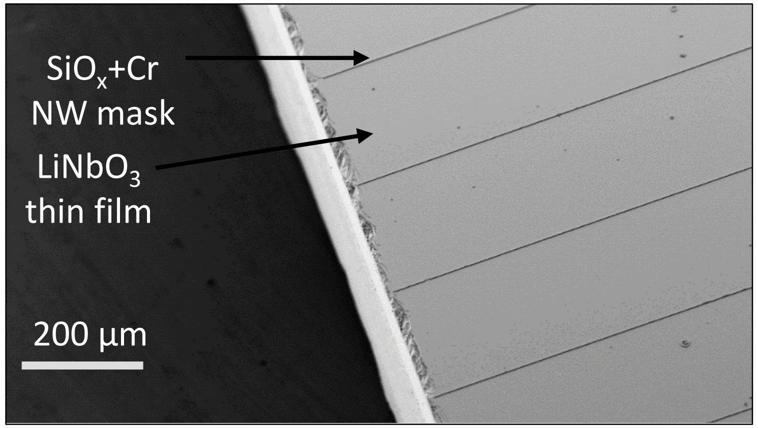


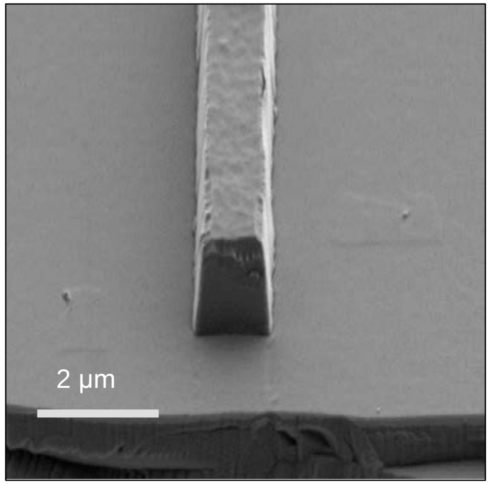
Sergeyev, A.; et al. ACS Photonics 2015, 2 (6), 687–691.

LiNbO3 on insulator LNOI

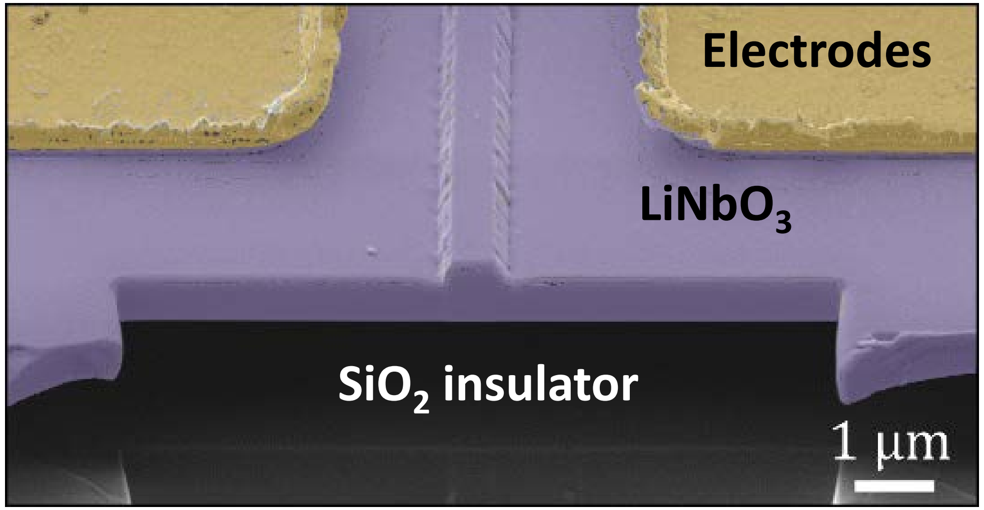
Process flow: Plasma etching (BRNC & First clean rooms facilities)







LNOI ridge waveguides



Escalé, M. R.; Pohl, D.; Sergeyev, A.; Grange, R. Optics Letters, 43, 1515, **2018**

Extreme electro-optic tuning in lithium niobate

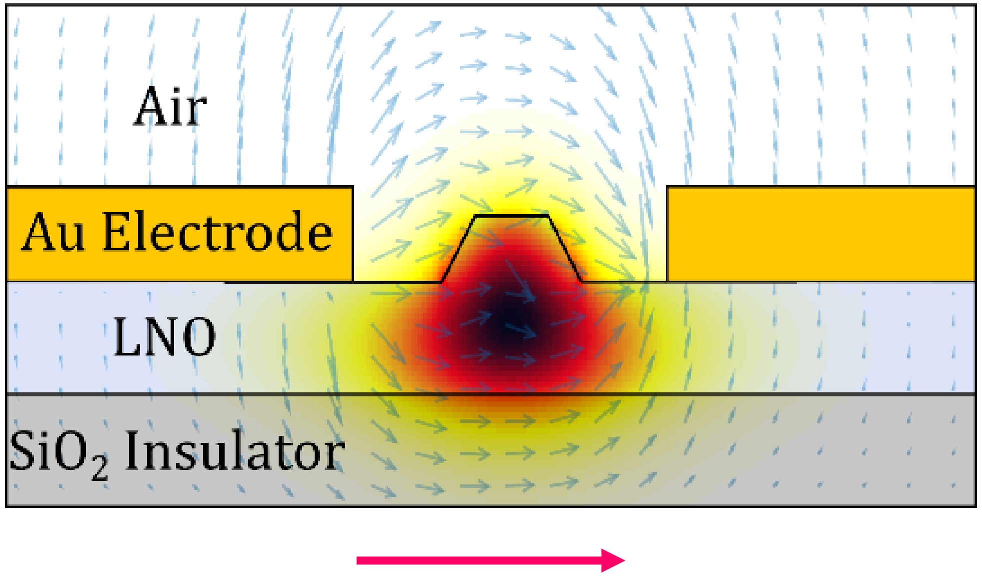
Pockel's effect

Change in the refractive index linearly proportional to the electric field

$$\begin{pmatrix} \Delta(1/n^2)_1 \\ \Delta(1/n^2)_2 \\ \Delta(1/n^2)_3 \\ \Delta(1/n^2)_4 \\ \Delta(1/n^2)_5 \\ \Delta(1/n^2)_6 \end{pmatrix} = \begin{pmatrix} 0 & -3.4 & 8.6 \\ 0 & 3.4 & 8.6 \\ 0 & 0 & 30.8 \\ 0 & 28 & 0 \\ 28 & 0 & 0 \\ -3.4 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}$$

Electro-optic tensor of $LiNbO_3$

Electro-optic tuning capabilities



Electric field has to be parallel to the z-crystal axis

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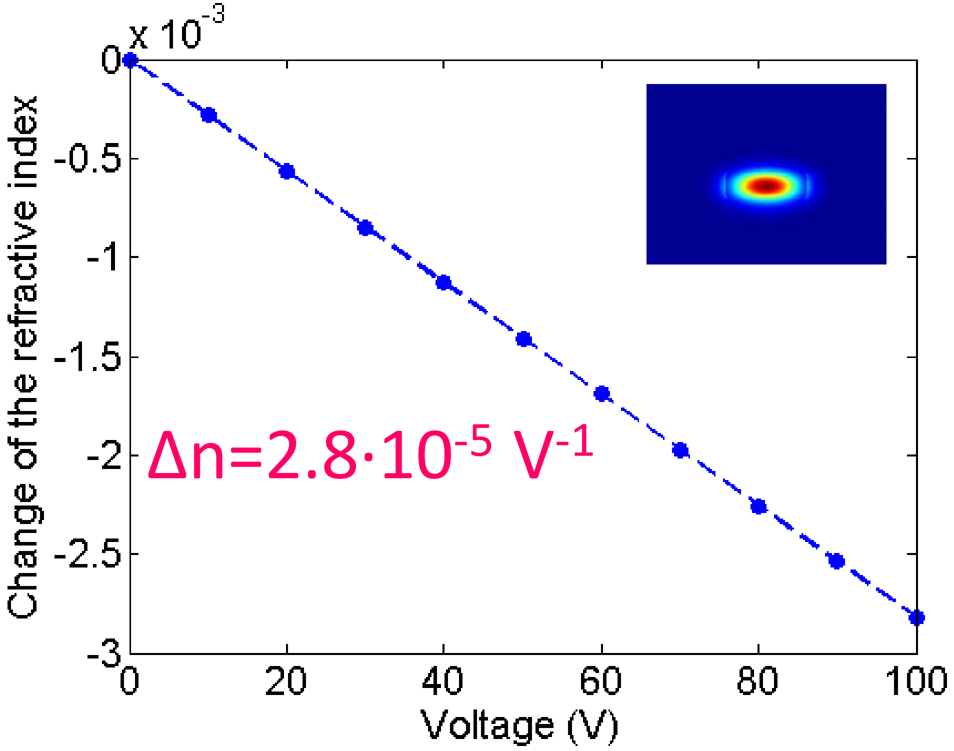
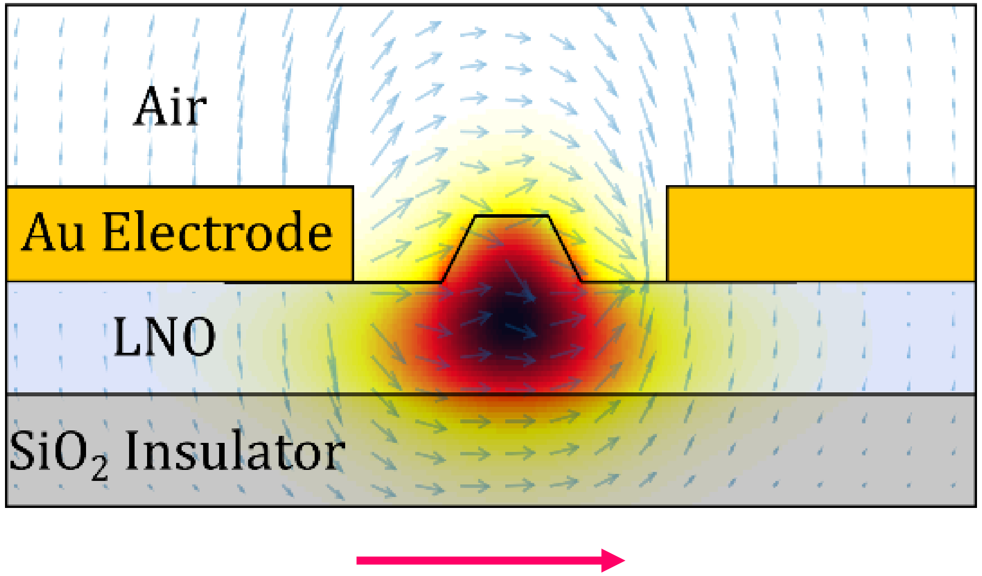
Pockel's effect

Theoretical change of the refractive index of TE00



Electro-optic tuning capabilities



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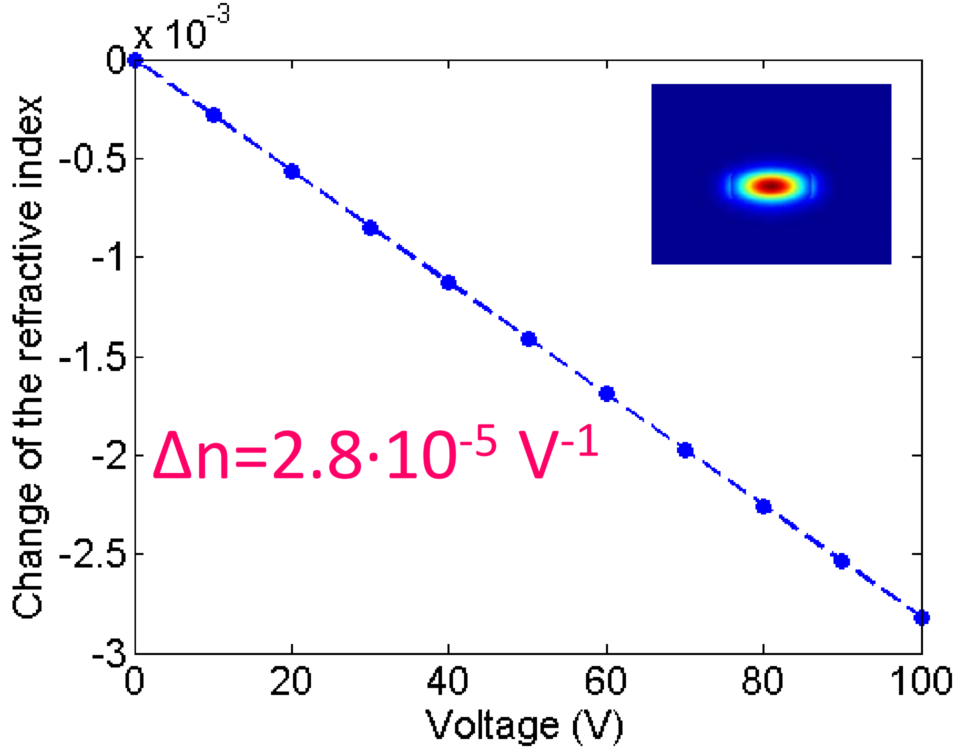
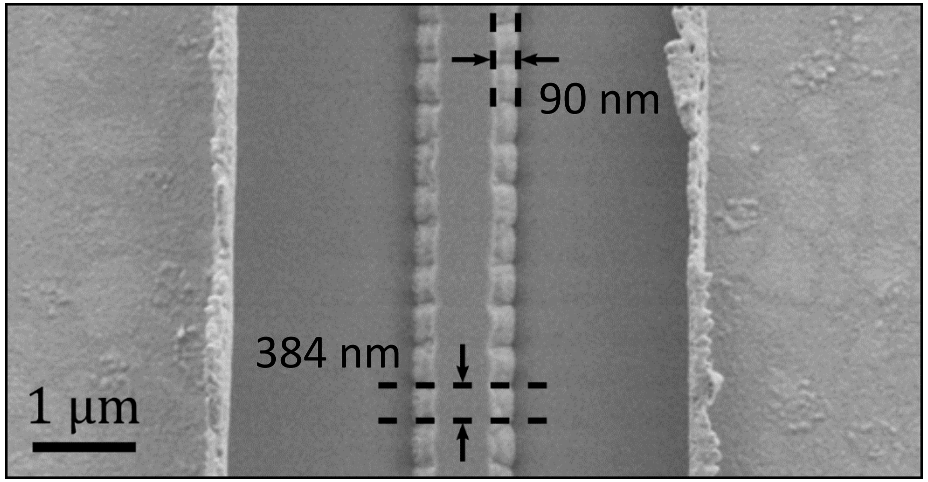


Distributed Bragg reflector

Multilayers of alternating materials with varying n, each layer causes a partial reflection



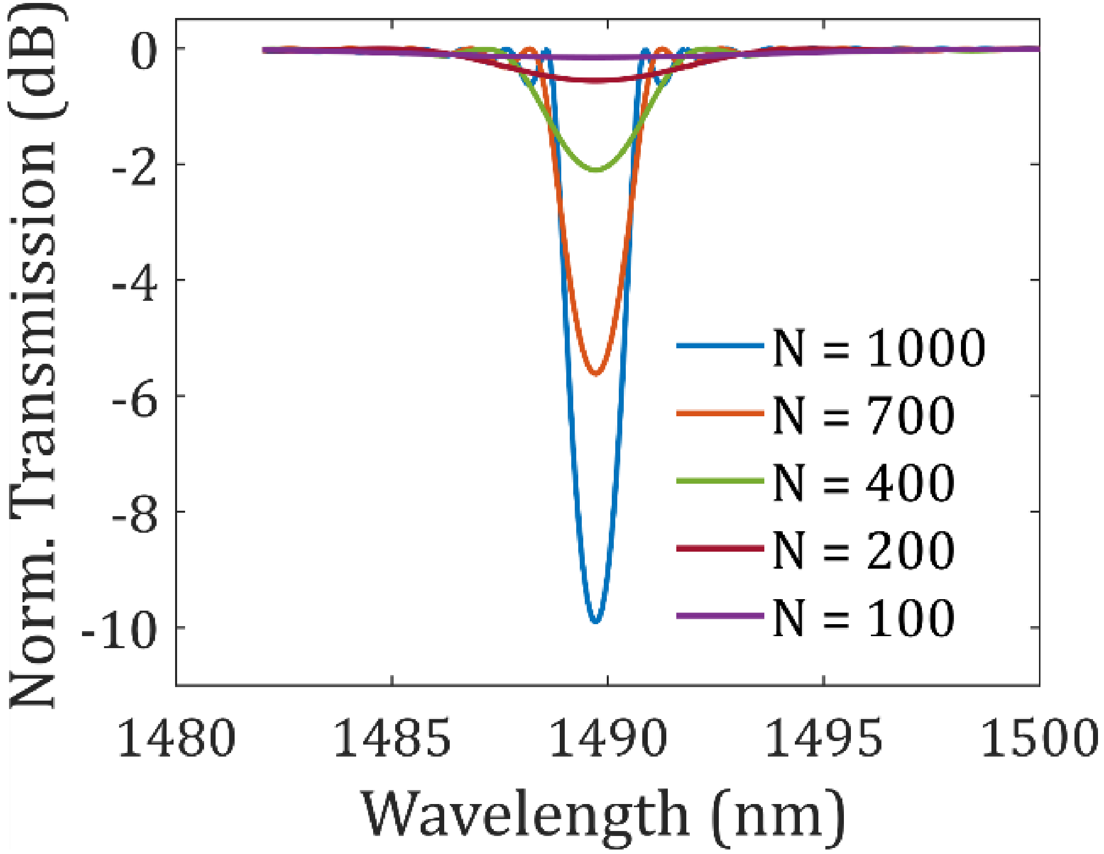
Period : 384 nm
Corrugation depth : 90 nm
Propagation losses:

α_{TE}=8.07 dB/cm
α_{TM}=3 dB/cm

Extreme electro-optic tuning in lithium niobate

Distributed Bragg reflector

Stop Band: Transmission Spectra



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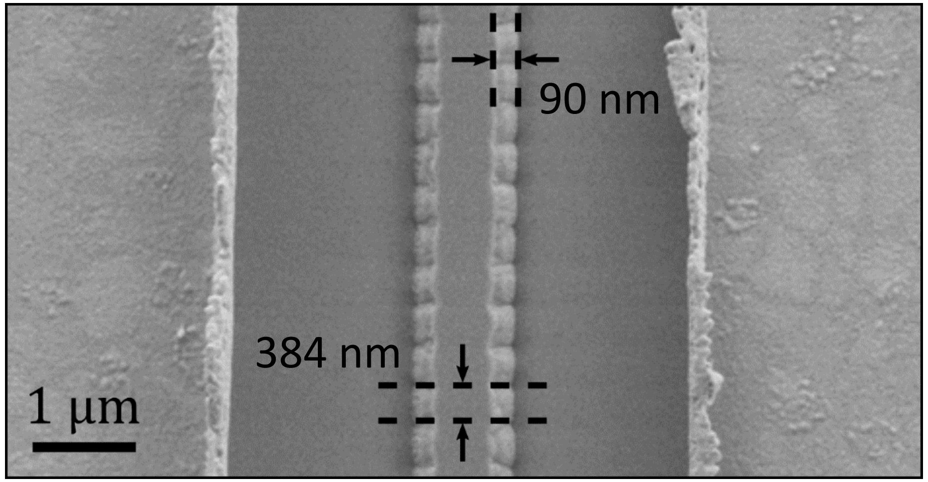

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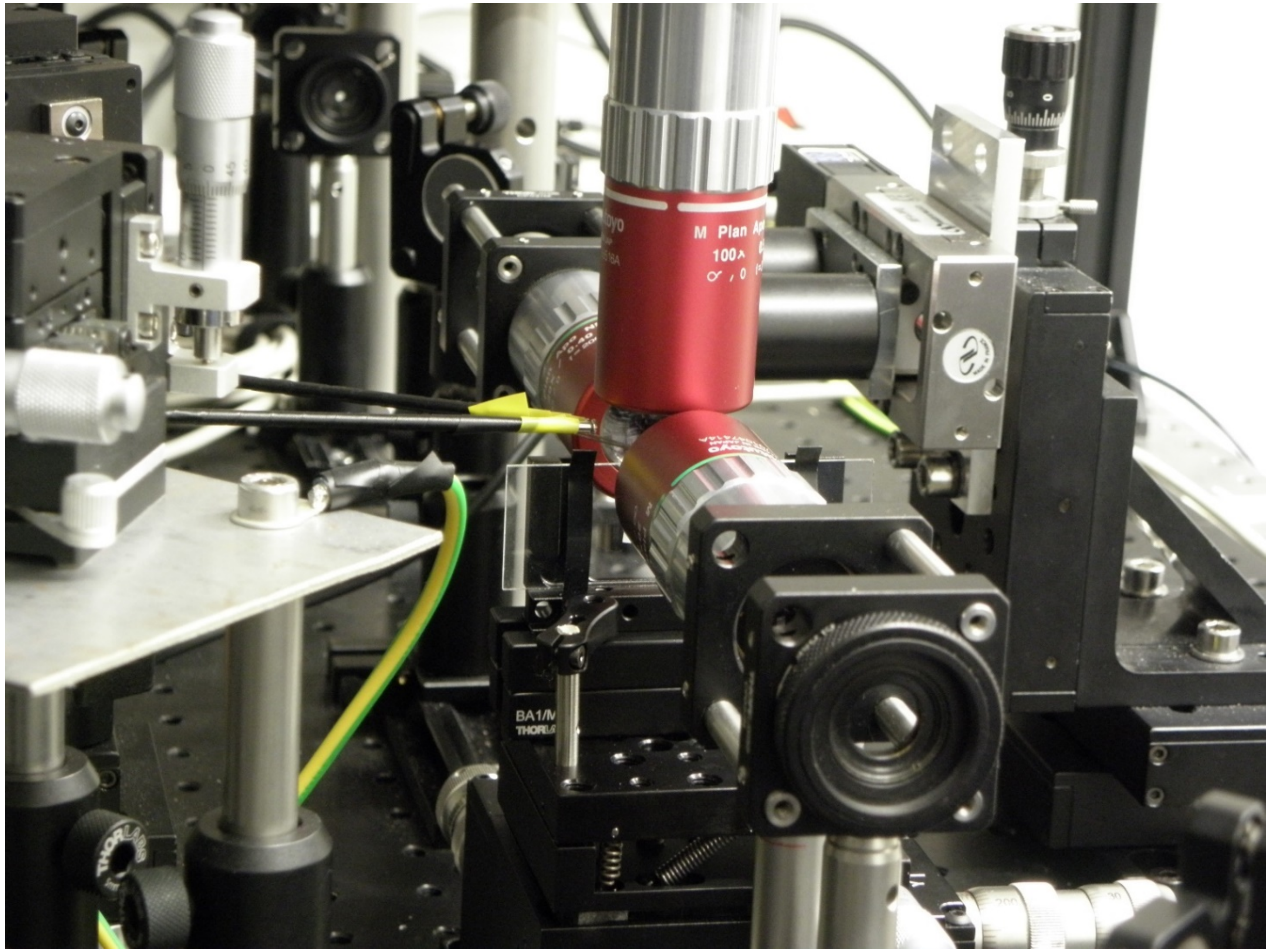

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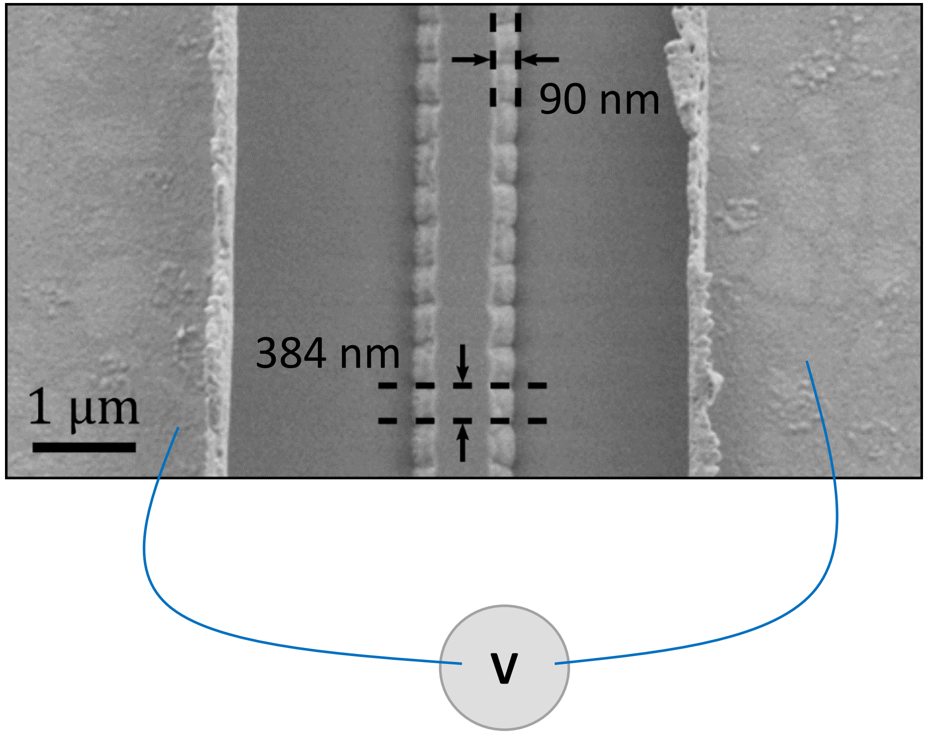

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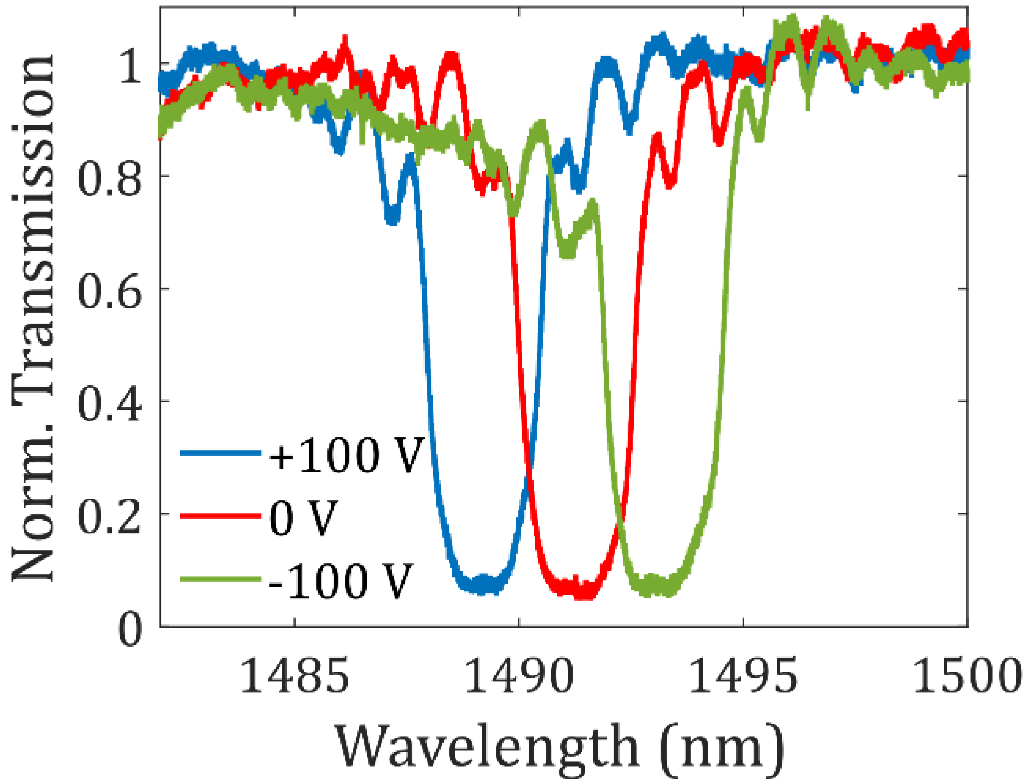
Extreme electro-optic tuning in lithium niobate

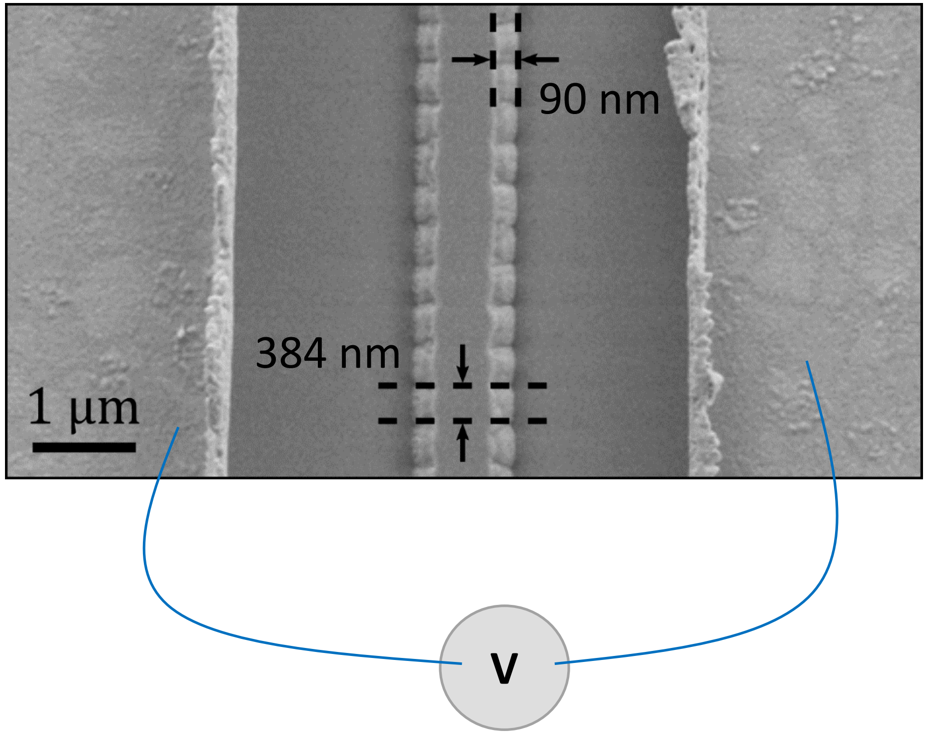
Wide tuning of the stop band



- R_{peak} 93.5 %
- 14 dB in transmission suppression

Distributed Bragg reflector

Multilayers of alternating materials with varying n, each layer causes a partial reflection



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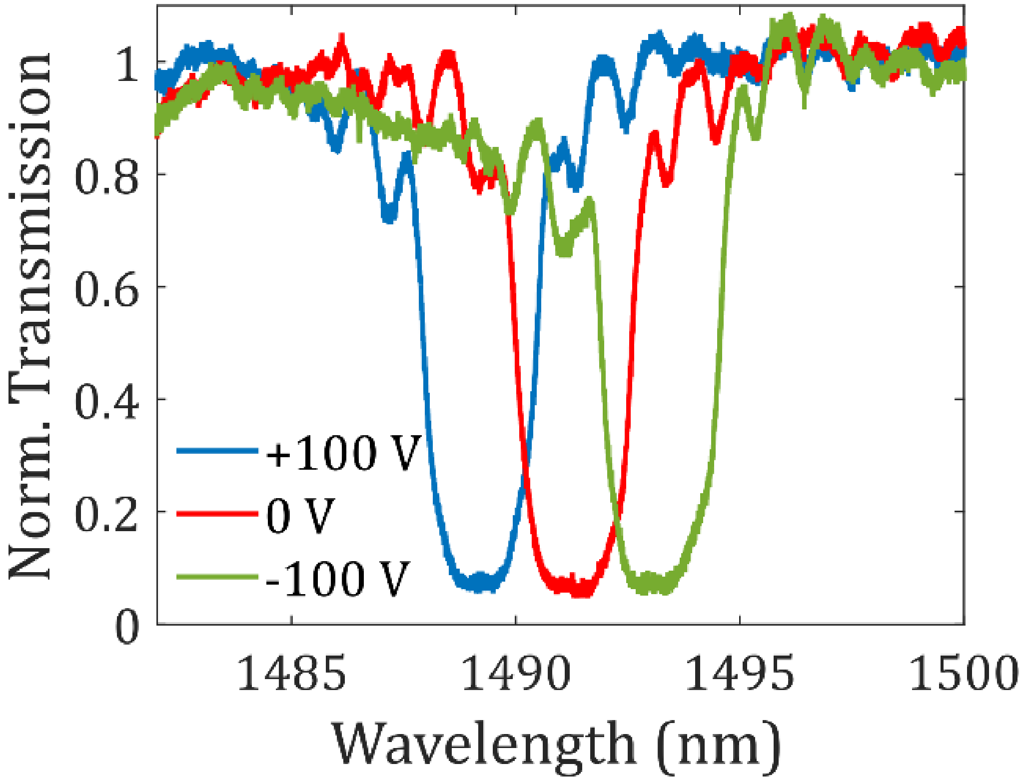

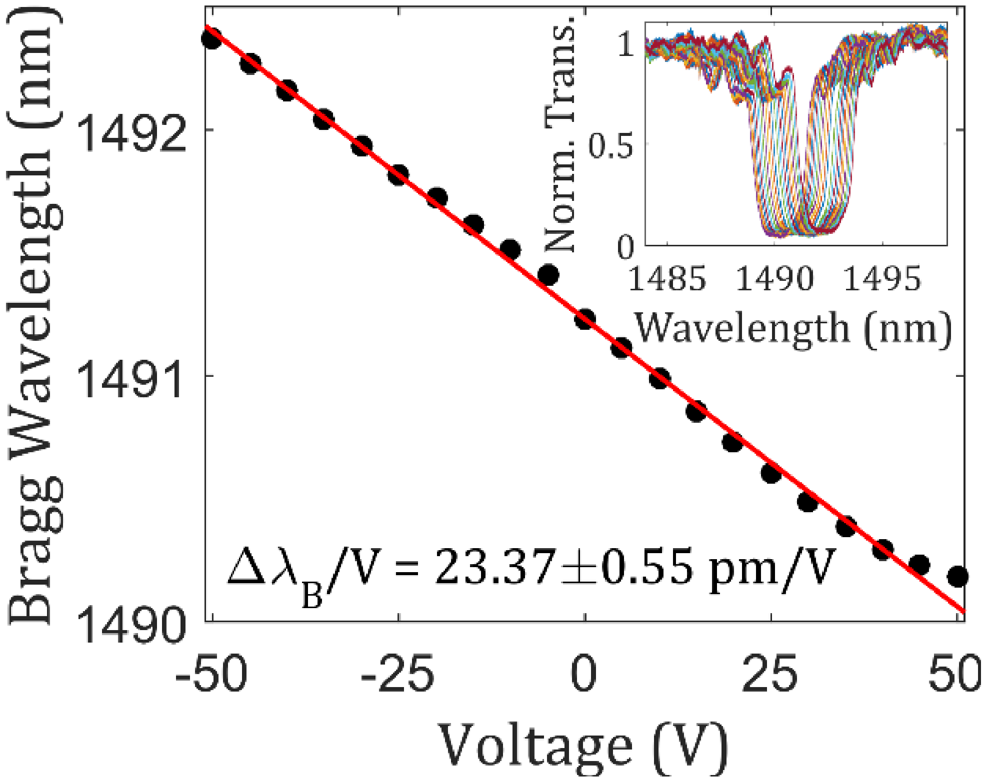

33 x more tuning than state-of-the-art devices !

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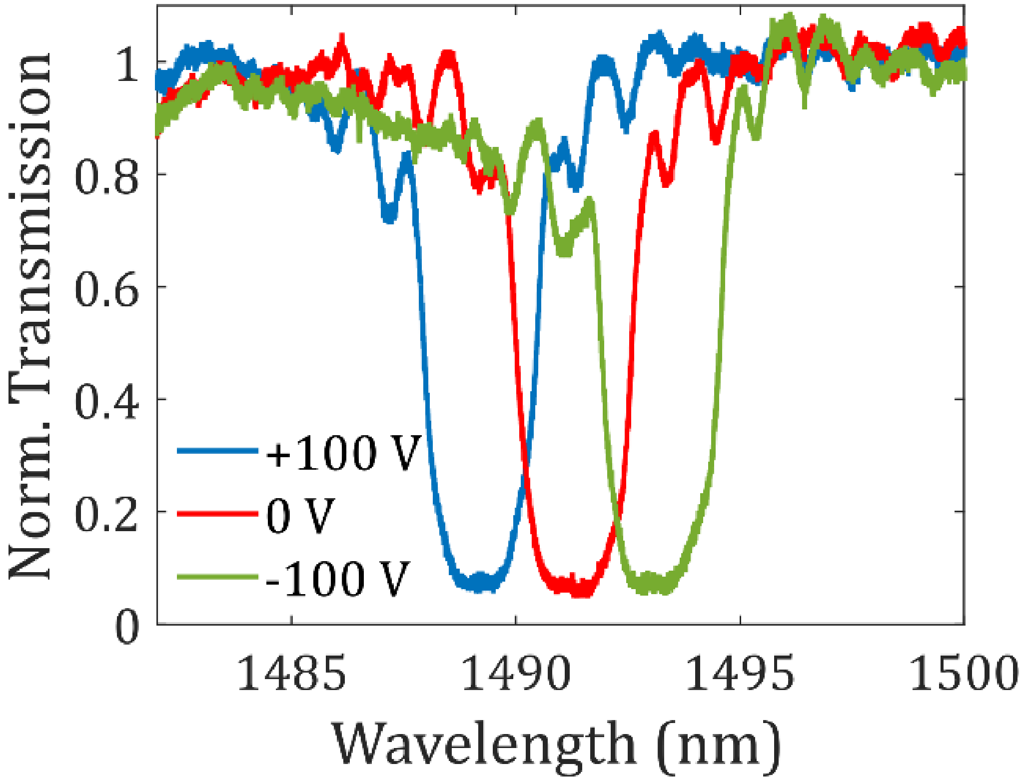

Insertion losses : 12.9 dB

Extinction ratio 14dB

Footprint: 10×500 μm^2

Bandwidth 2nm

33 x more tuning than state-of-the-art devices !

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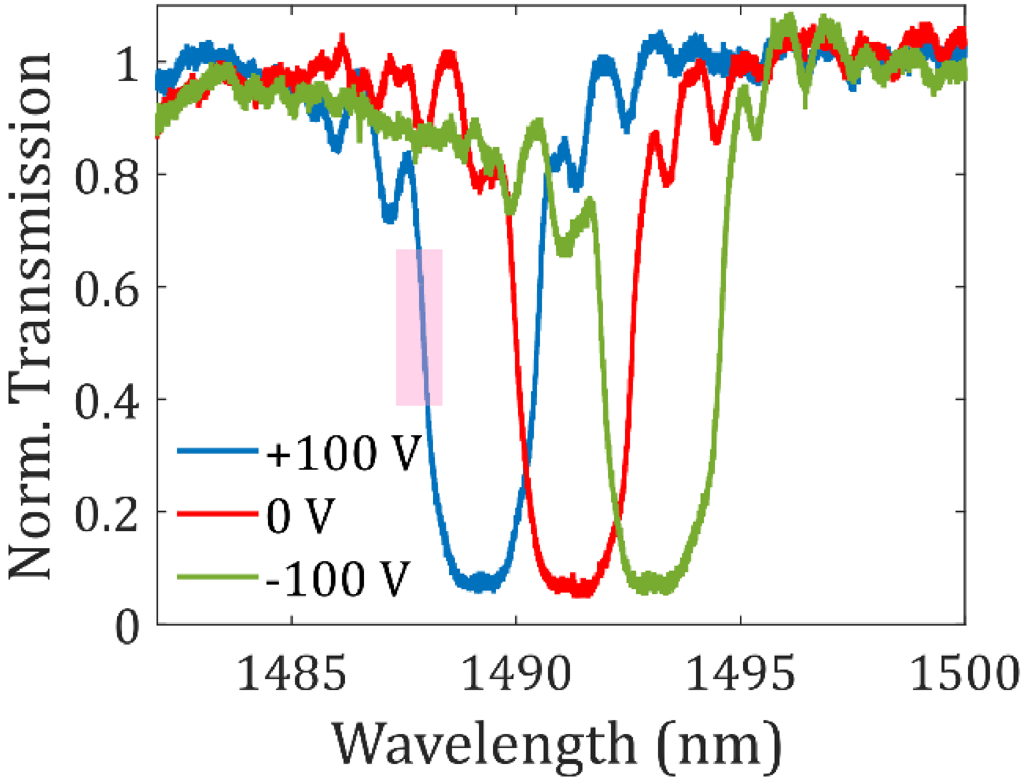
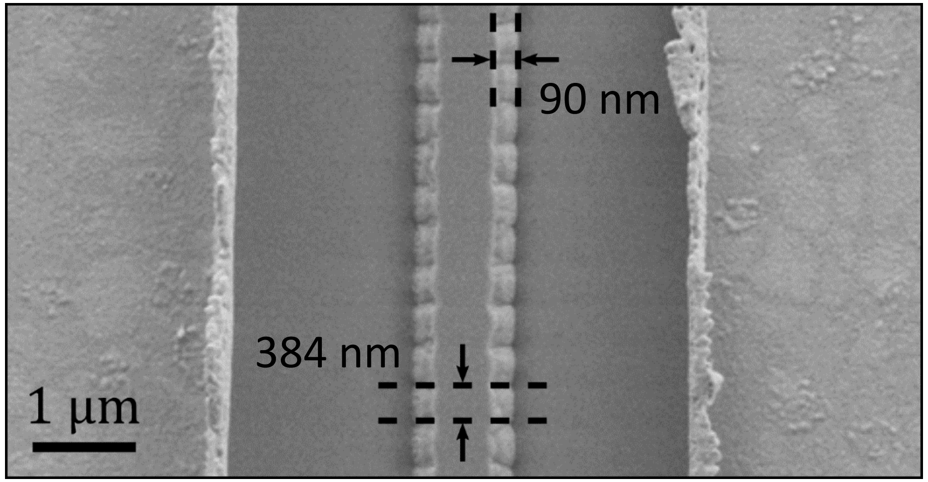
Wide tuning of the stop band





electrode gap is 4.5 µm

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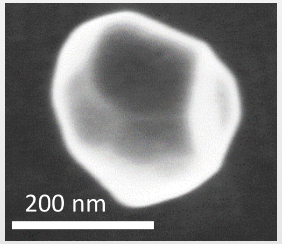
$\chi^{(2)}$ materials at small scale

$\chi^{(2)}$ Building blocks

$BaTiO_3$



Timpu,et al. ACS Photonics, 4, 2017.

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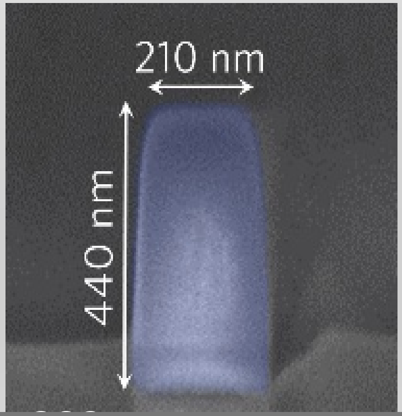
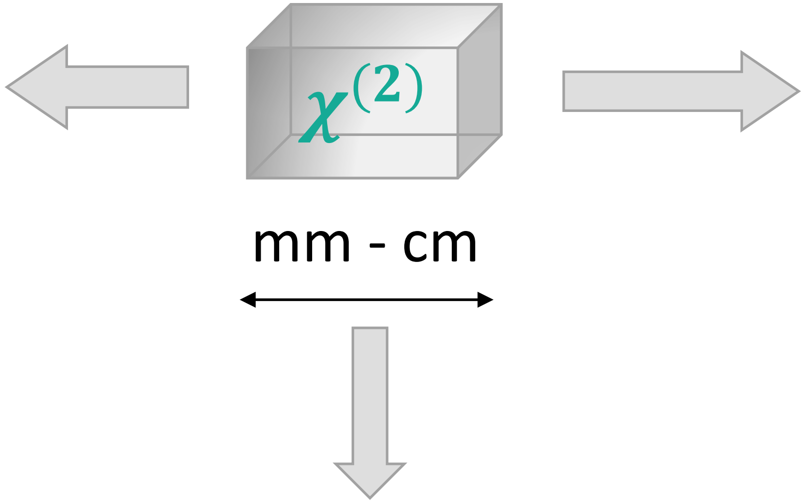
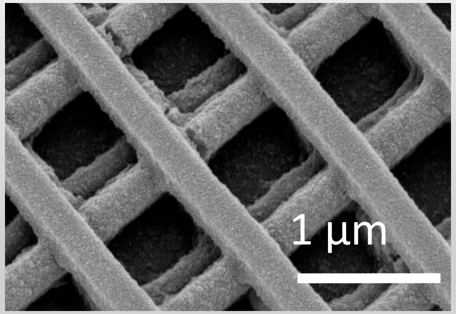


M. Timofeeva, et al. , Nano Letters, accepted May 17, 2018



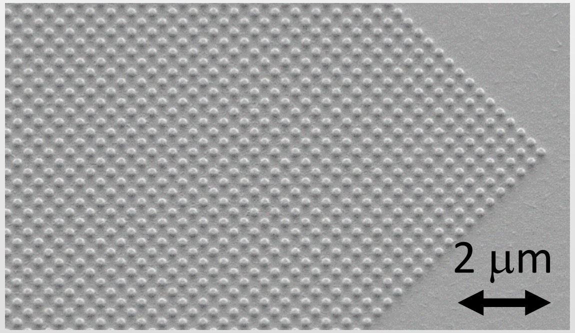
Bottom-up processing

Wide surface area photonic crystal

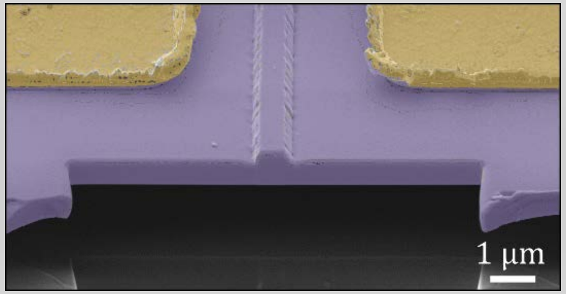


Top-down fabrication

Flat photonic structures



Integrated devices



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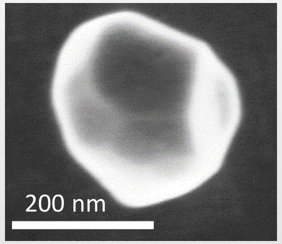

Timpu,et al. ACS Photonics, 4, 2017.
Renaut et al., Nano Lett., 2019

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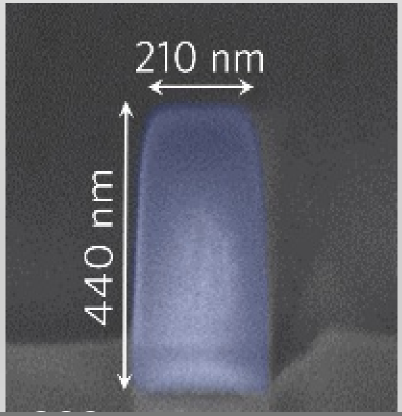
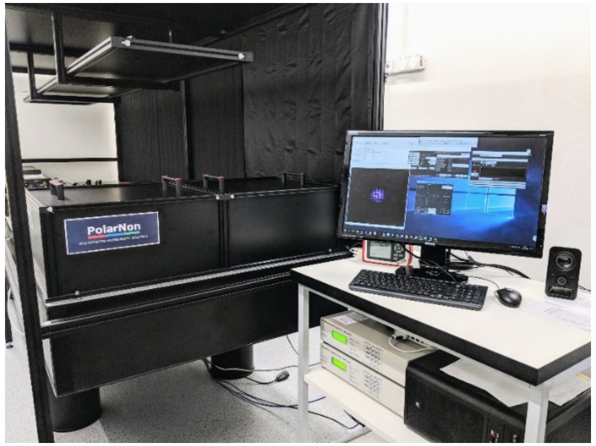


M. Timofeeva, et al. , Nano Letters, accepted May 17, 2018

Super-Polar microscope



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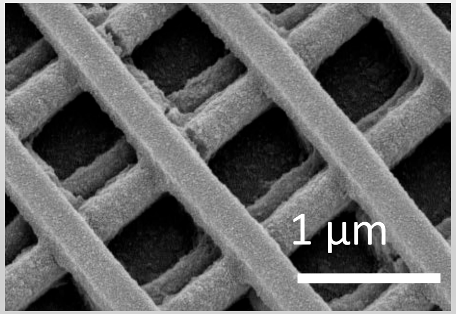

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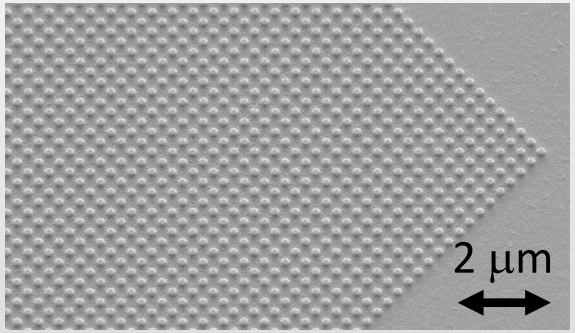

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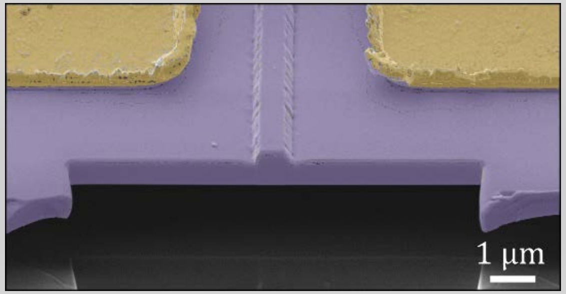

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