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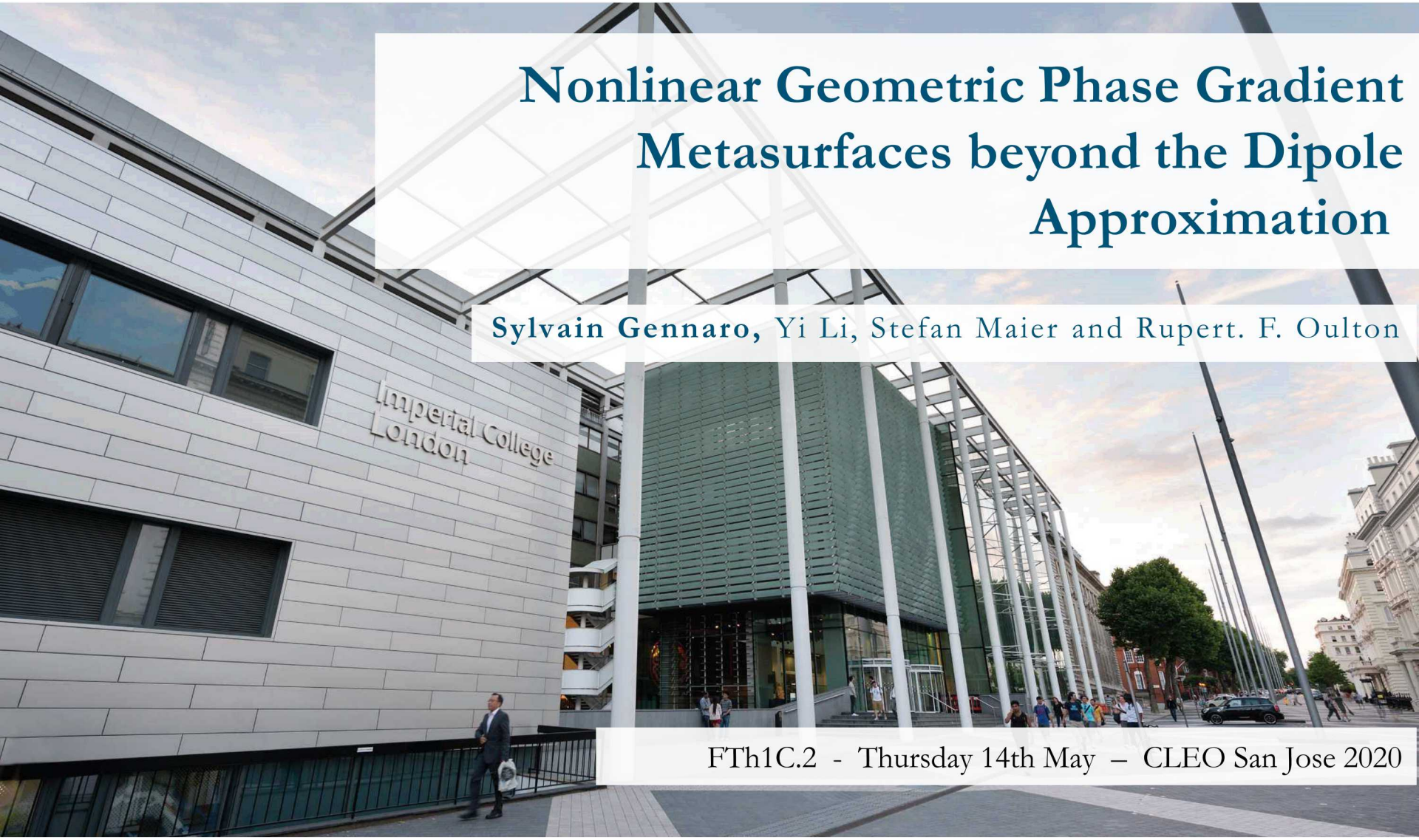

Nonlinear Geometric Phase Gradient Metasurfaces beyond the Dipole Approximation

Sylvain Gennaro, Yi Li, Stefan Maier and Rupert. F. Oulton

FTh1C.2 - Thursday 14th May – CLEO San Jose 2020

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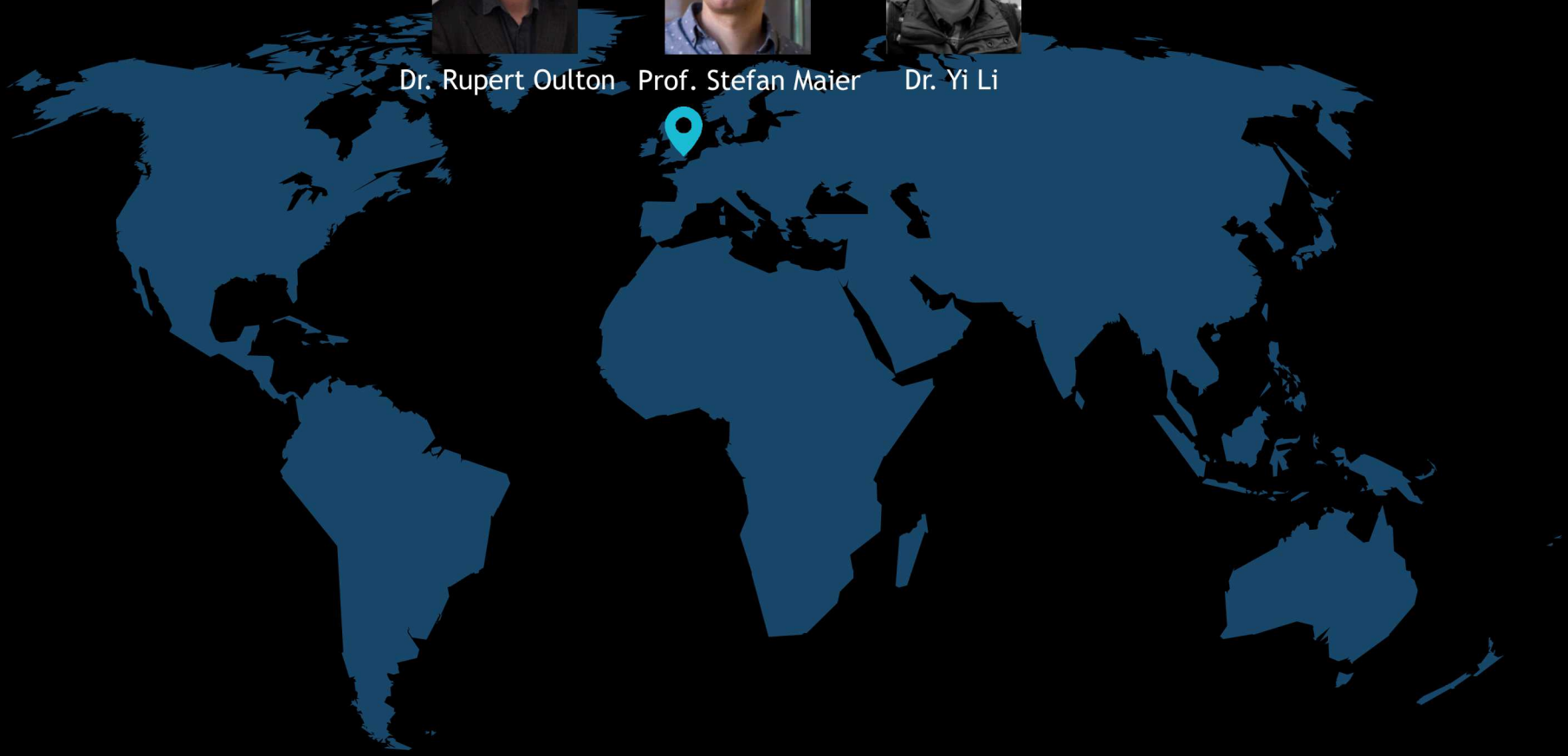
Dr. Rupert Oulton Prof. Stefan Maier Dr. Yi Li



This w… …of Materials Sciences and Engineering and performed, in part, at the Center for Integr… …y (DOE) Office of Science. Sandia National Laboratories is a multi mission … …wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Outlines

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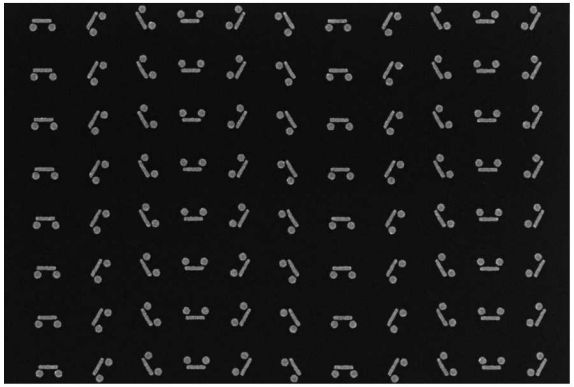
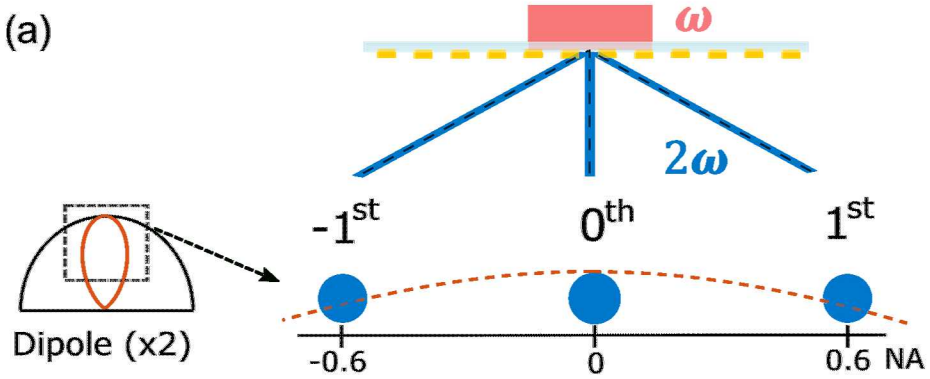
What is a Nonlinear Geometric Phase Gradient Metasurface?



How does high-order antenna modes impacts on a metasurface's geometric phase



Approach for phase engineering in metasurfaces

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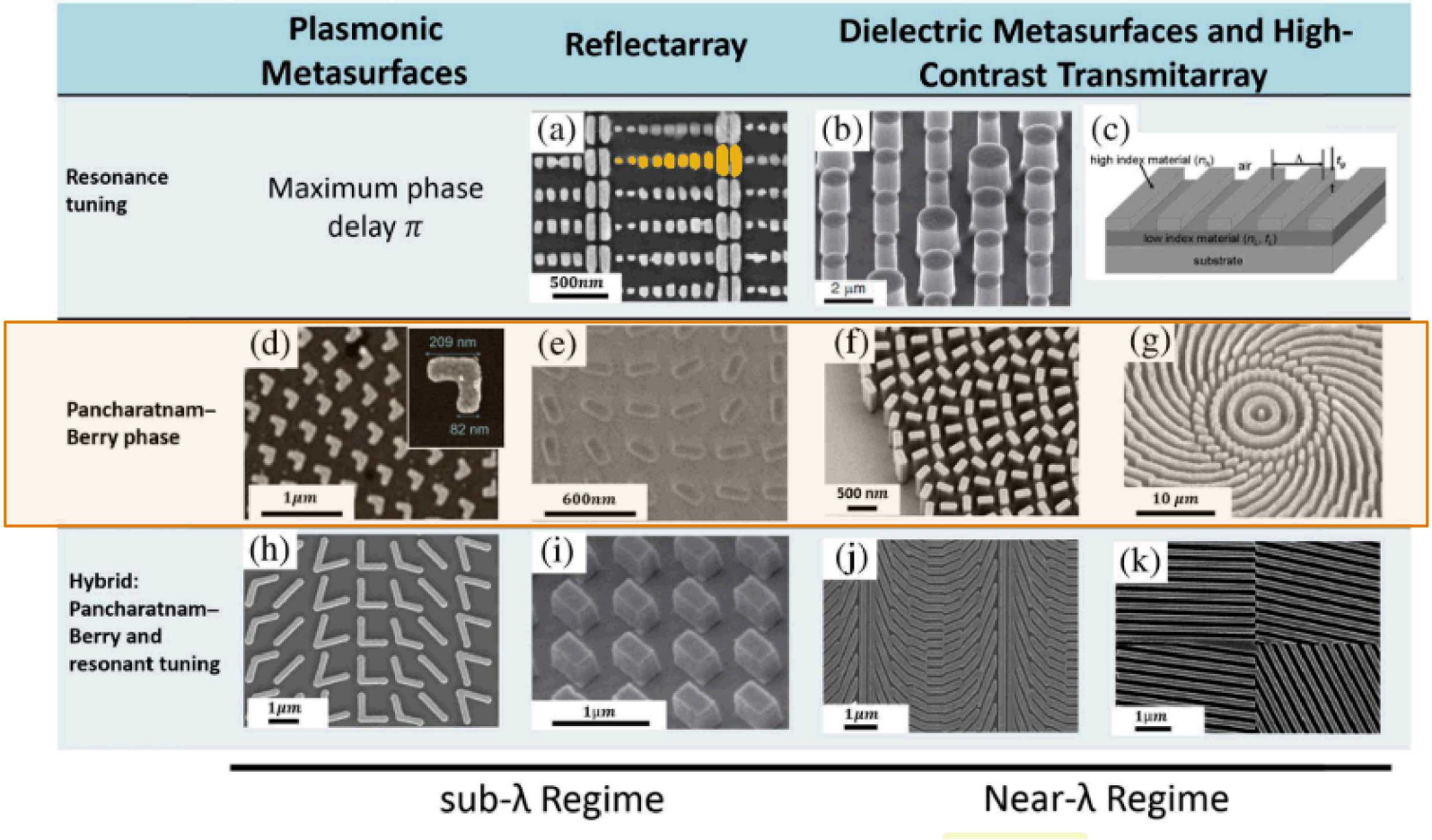
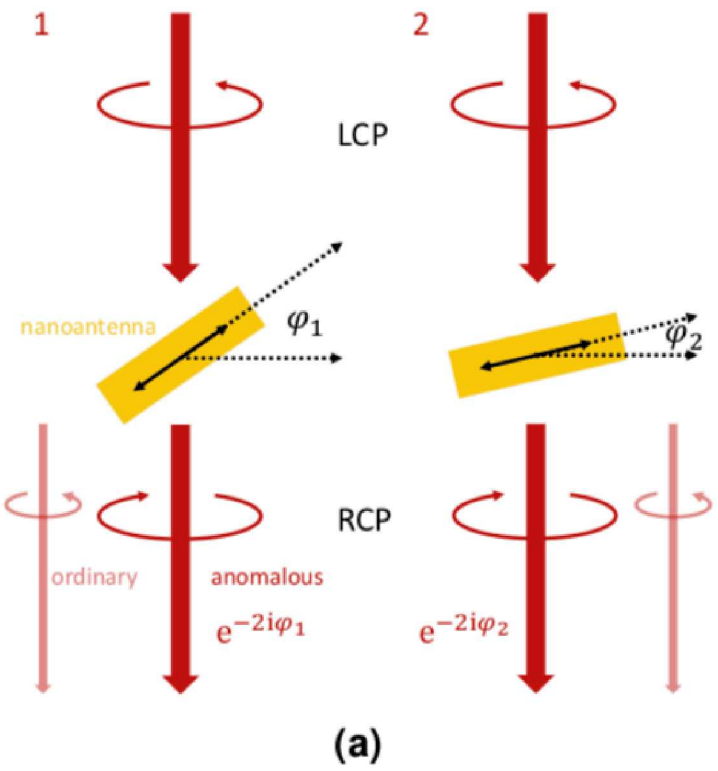


- The shape, size and orientation of optical antennas defines an optical phase of the metasurface for wavefront engineering.

Genevet, P., Capasso, F., Aieta, F., Khorasaninejad, M. & Devlin, R. Optica 4, 139 (2017)

Pancharatnam – Berry (PB) Phase

- For **circularly polarized light** of helicities σ = **1 (LCP),** and σ = **-1 (RCP)**, we have



Linear

$$\psi = (\sigma_{in} - \sigma_{out})\phi$$

Nonlinear

$$\text{SHG}: \quad \psi^{SHG} = (2\sigma_{in} - \sigma_{out})\phi$$

$$\text{THG}: \quad \psi^{THG} = (3\sigma_{in} - \sigma_{out})\phi$$

$$\text{FWM}: \psi^{FWM} = \left(2\sigma_{in}^{1} - 1\sigma_{in}^{2} - \sigma_{out}\right)\phi$$

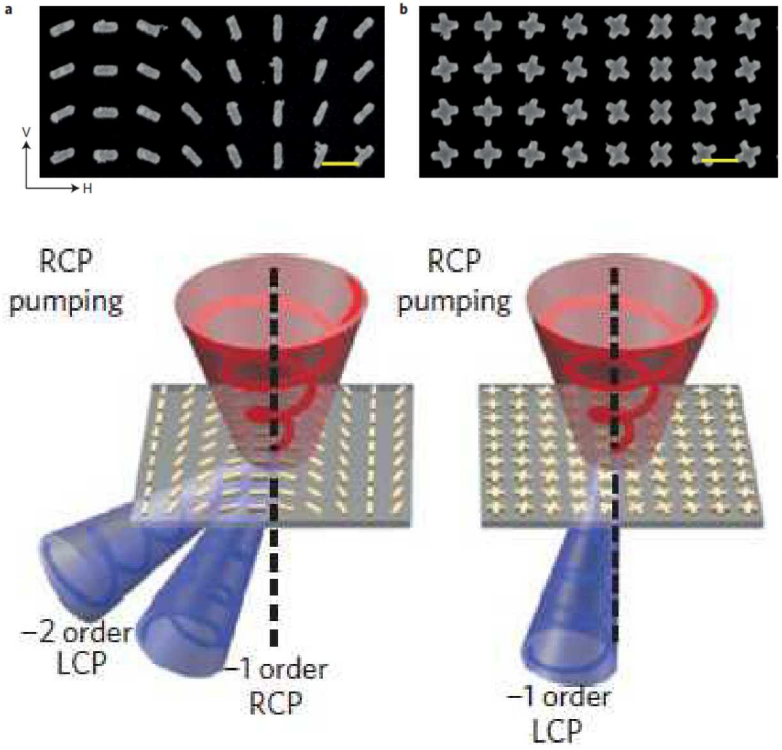
Berry, M. V. The Geometric Phase. *Sci. Am.* **1988**, *259*, 46-52.

Li et al. Nature Review Material 2. 17010 (2017)

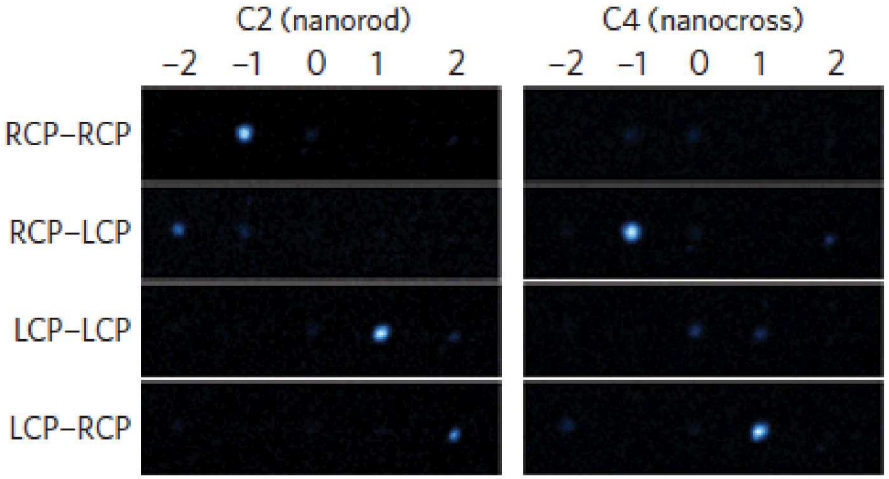
For a full derivation for SHG , please see the work by Tymchenko et al. PRL 115, 207403 (2015)

THG signals from metasurfaces with a phase gradient

- Like a grating, the periodicity of a metasurface generates diffraction orders

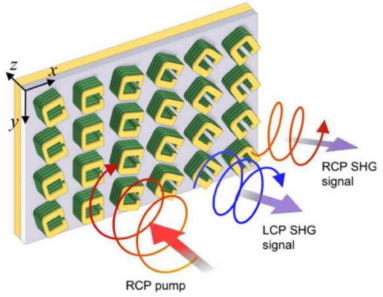


Guixin Li et al. Nature Materials.
Vol 14, 607–612 (2015)



THG diffraction orders

- For additional references, please see the work by Tymchenko et al. PRL 115, 207403 (2017)



Outlines

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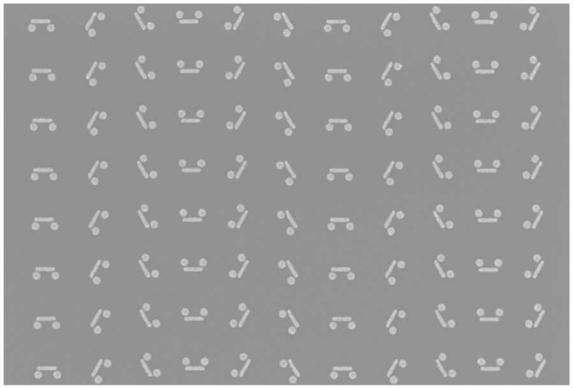
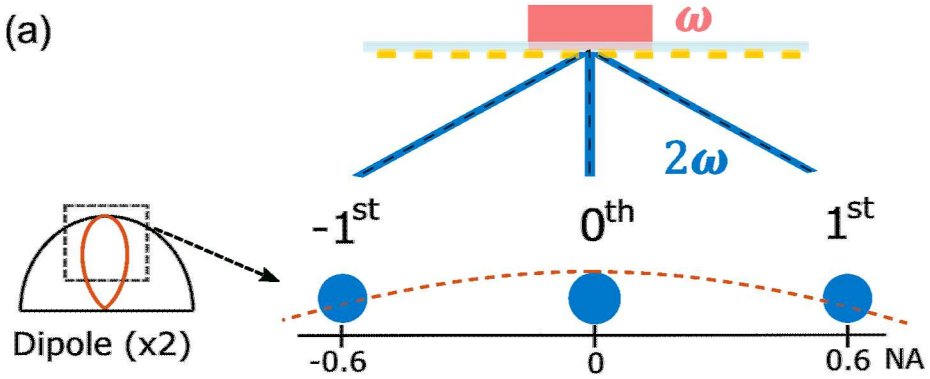
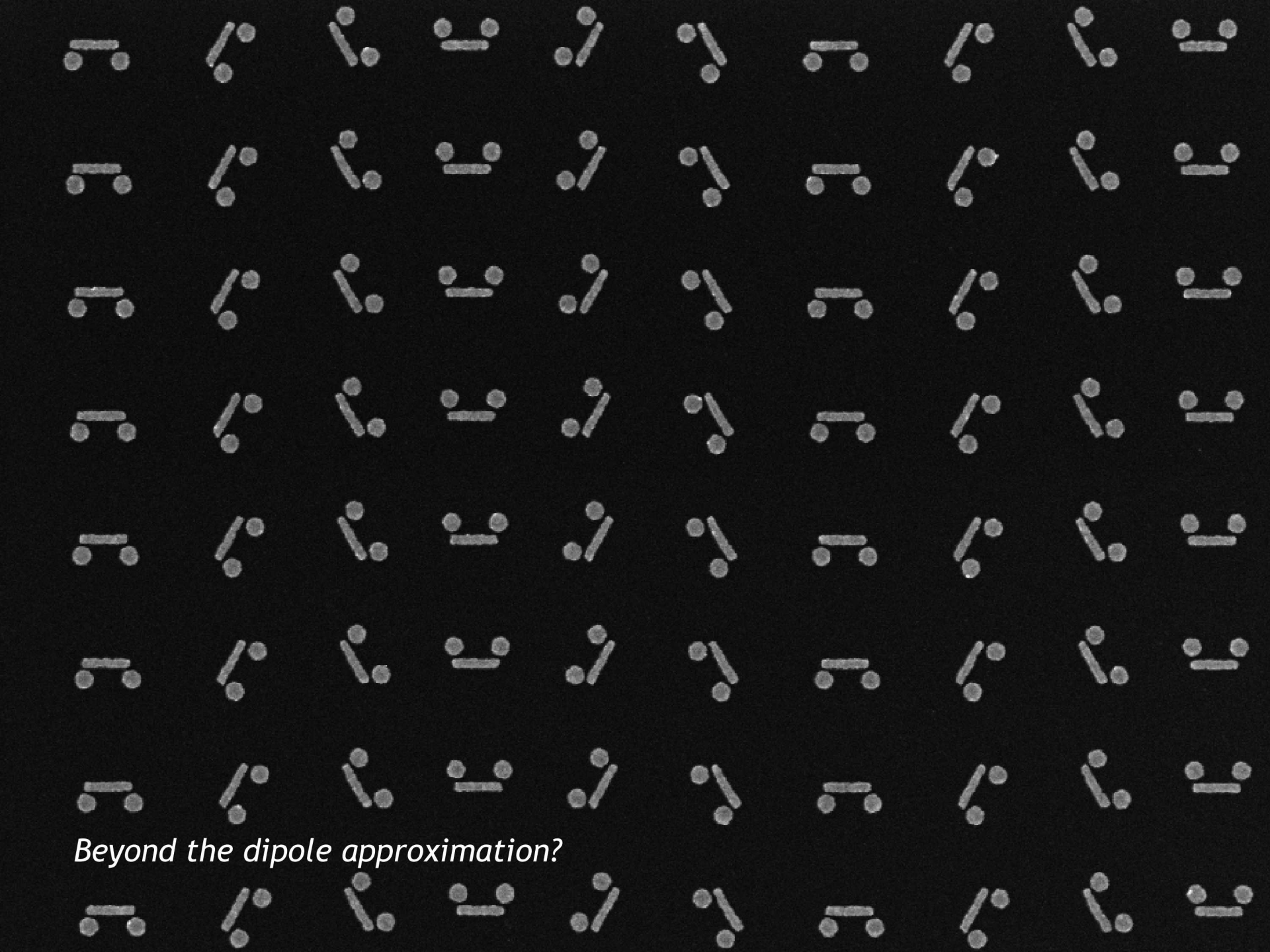
What is a Nonlinear Geometric Phase Gradient Metasurface?



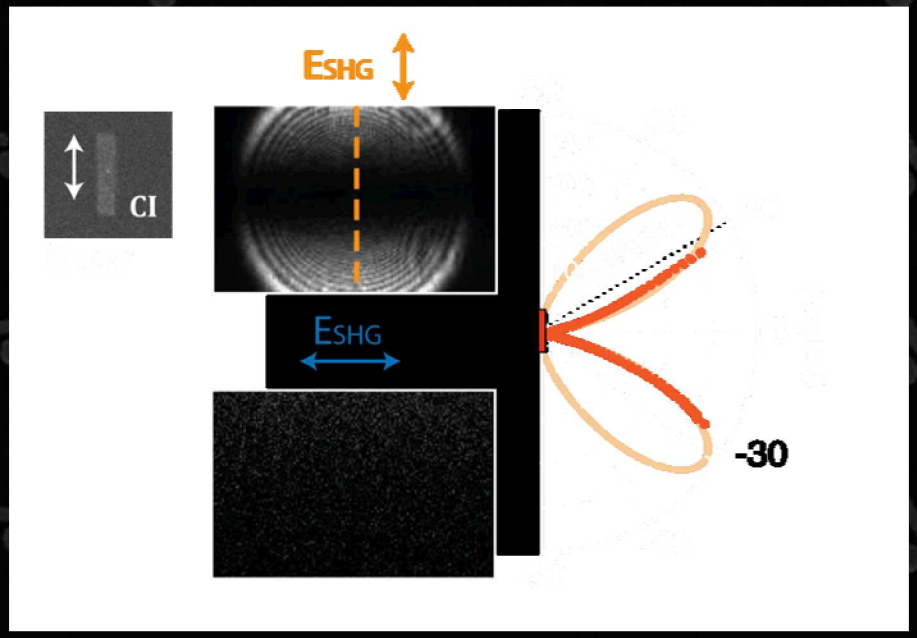
How does high-order antenna modes impacts on a metasurface's geometric phase

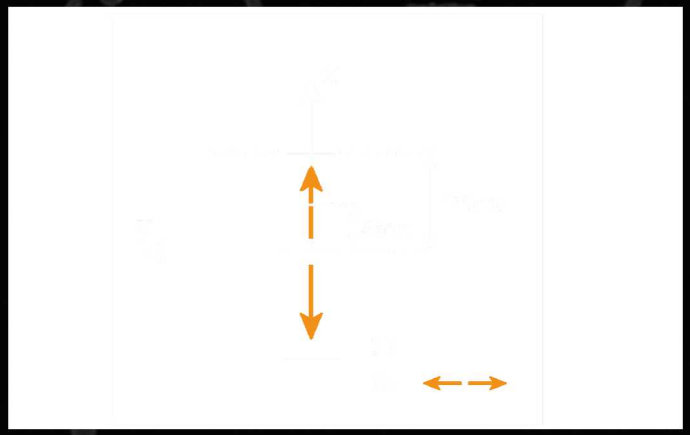


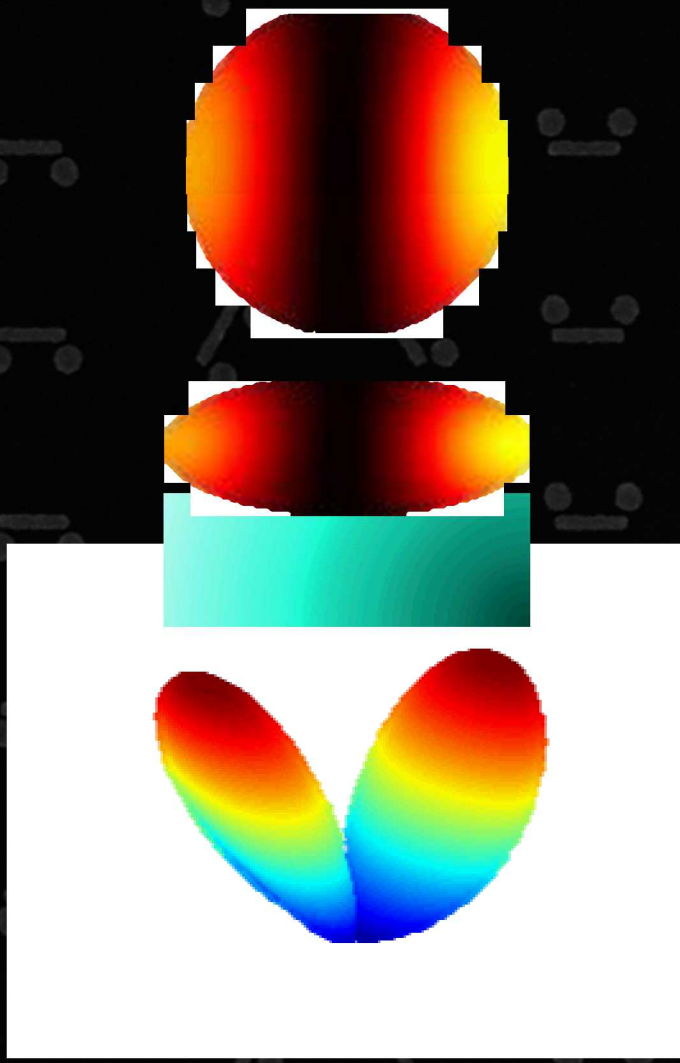


Beyond the dipole approximation?

SHG Radiation Pattern of a bar antenna

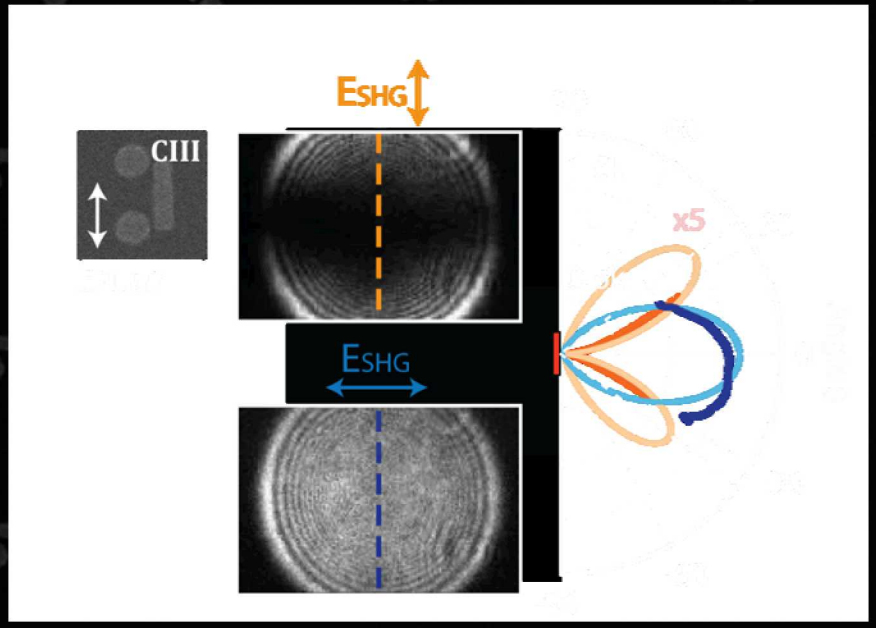


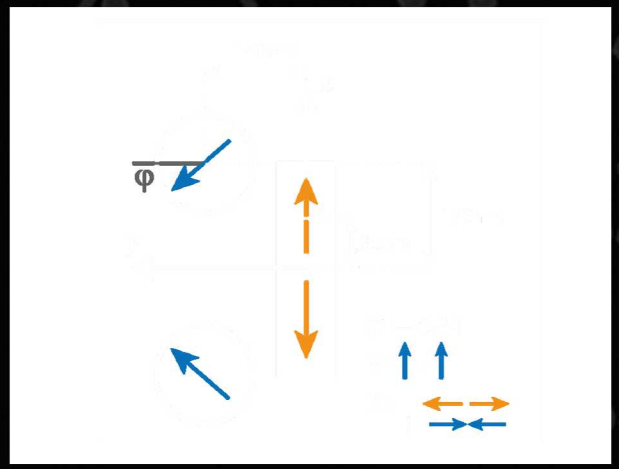


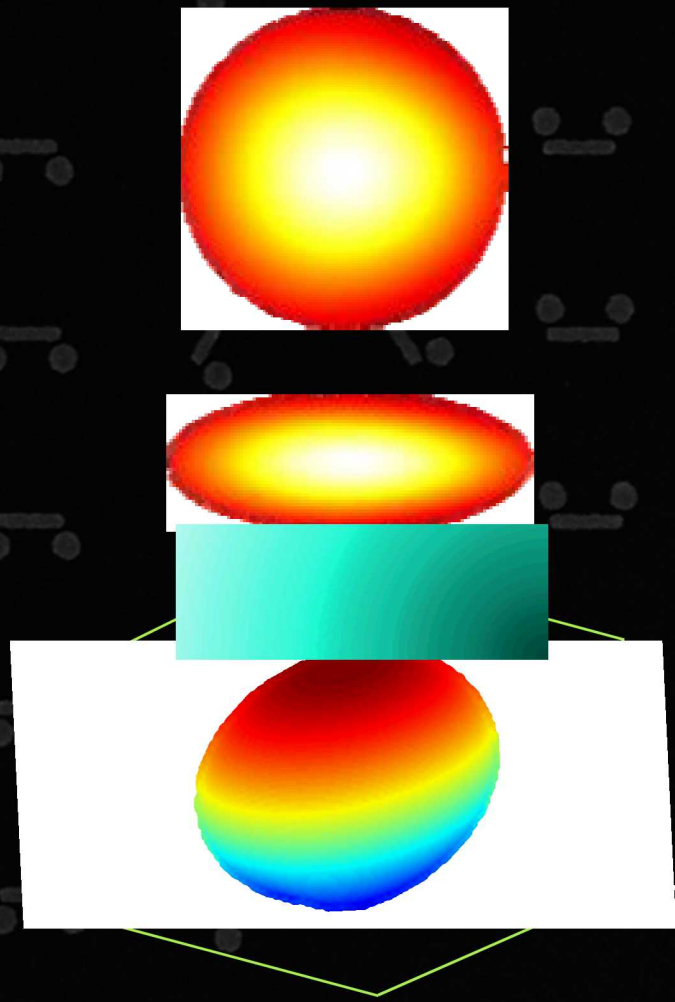


SHG : Gennaro et al. Nano Lett. 2016, 16, 8, 5278-5285

SHG Radiation Pattern of a bar and disk antenna







SHG : Gennaro et al. Nano Lett. 2016, 16, 8, 5278-5285

Phase Gradient Metasurface : Our work

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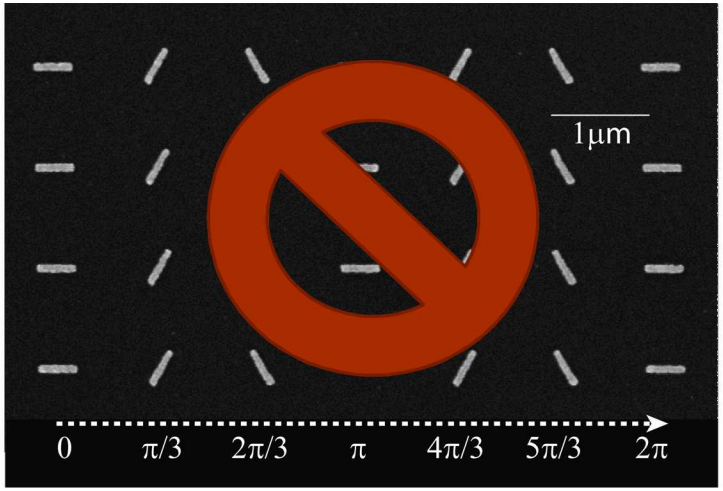
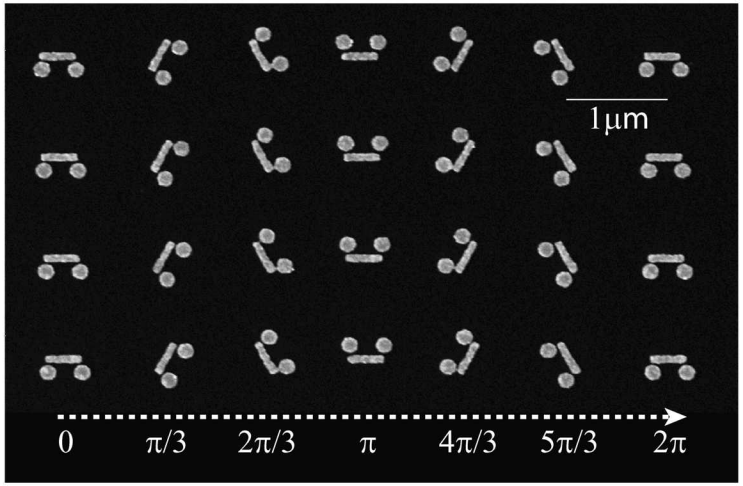
- Second harmonic generation from two metasurfaces made with :
  - A) Quadrupole antenna modes
  - B) Dipole – like antenna modes

Symmetry – disallowed process!





For more information on symmetry rules in PB phase gradient metasurface, please see the work by :

- Li G. et al. Nature Review Material 2. 17010 (2017)
- Chen et al. PRL 113, 033901 (2014)

Linear Transmission Spectra

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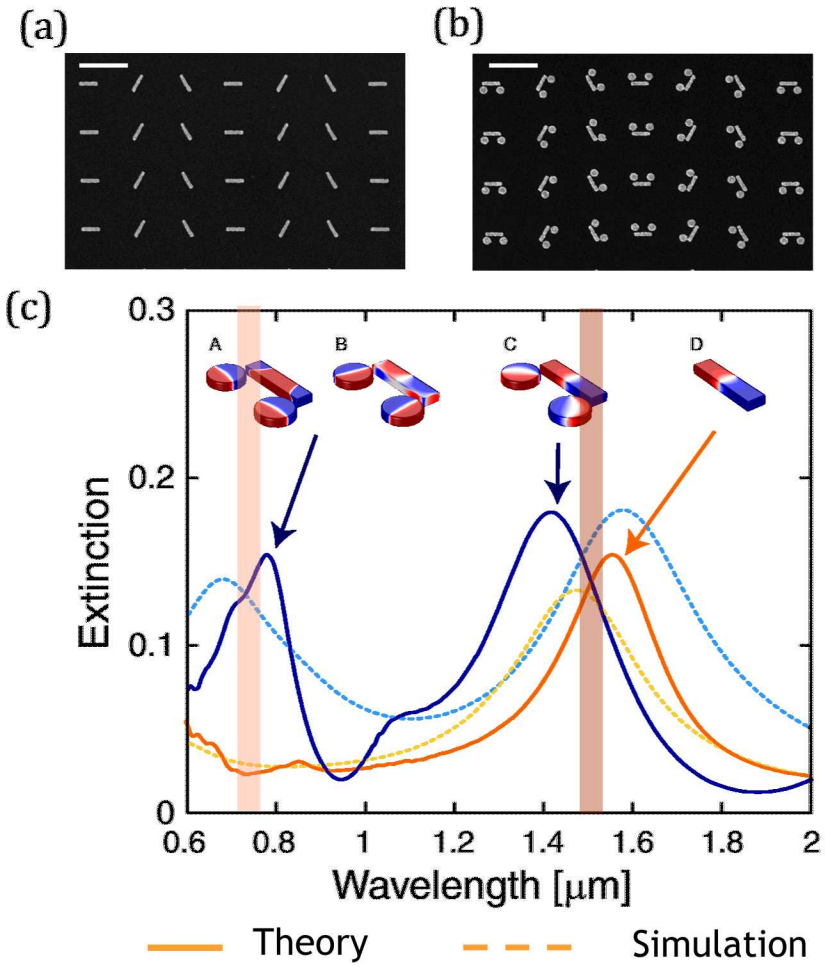
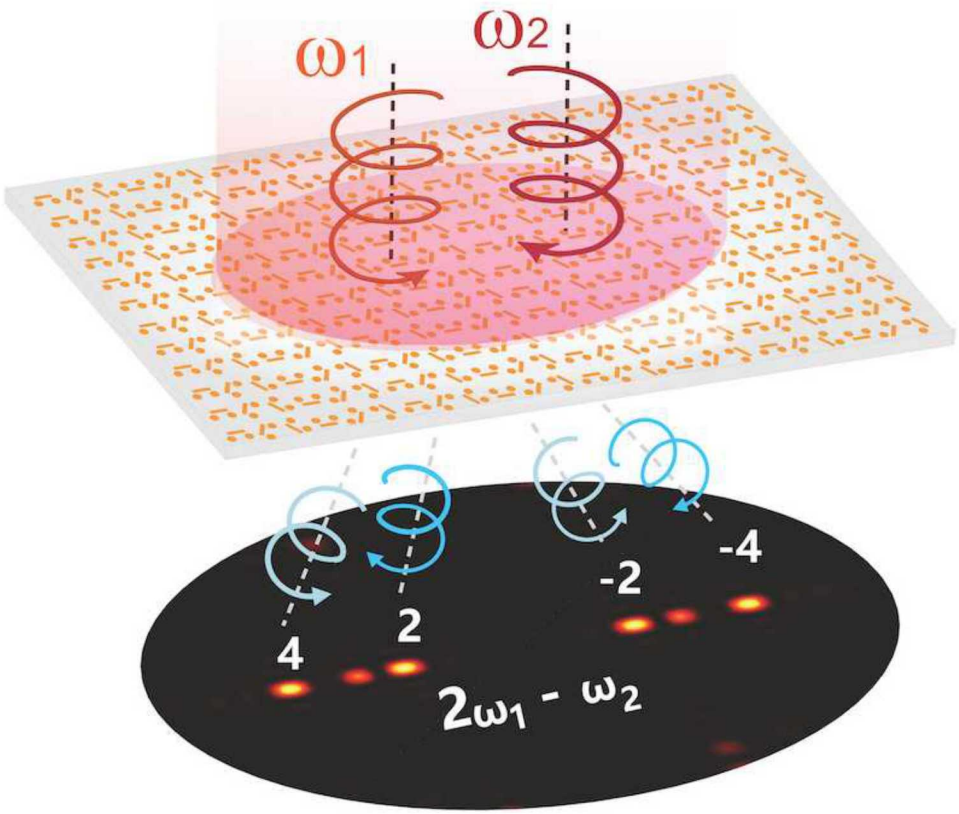


Bar: length = 370 nm, width = 75 nm, height = 40 nm. Disks : radius = 150 nm, height = 40 nm. Gap widths are 20 nm. The lattice period is 1 μm in both directions.

SHG : Gennaro et al. Nano Lett. 2016, 16, 8, 5278-5285

PB phase : Gennaro et al. ACS Photonics 2019, 6, 9, 2335-2341

Nonlinear Diffraction Orders Measurement



PB phase : Gennaro et al. ACS Photonics 2019, 6, 9, 2335-2341

Grating equation : point source approximation

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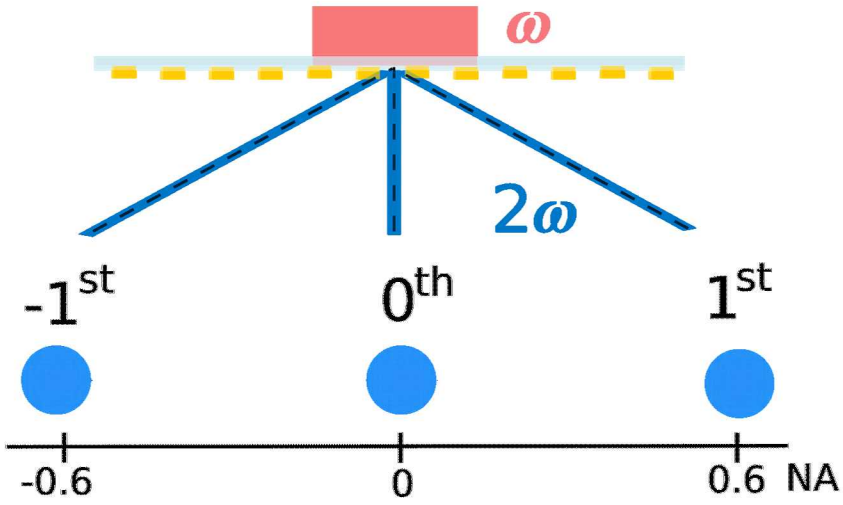
When neighboring antennas' radiation is in phase along x, we have :
wavevector **k**, spacing **a**, integer **p**

$$k_x a = 2\pi p,$$

With a geometric phase difference expressed as :

$$\psi_{m,n} - \psi_{m-1,n} = \Delta\sigma_{NL}\frac{2\pi}{N}. \quad (\mathrm{N} = 6)$$

SHG : $\Delta\sigma_{NL} = (2\sigma_{in} - \sigma_{out})$



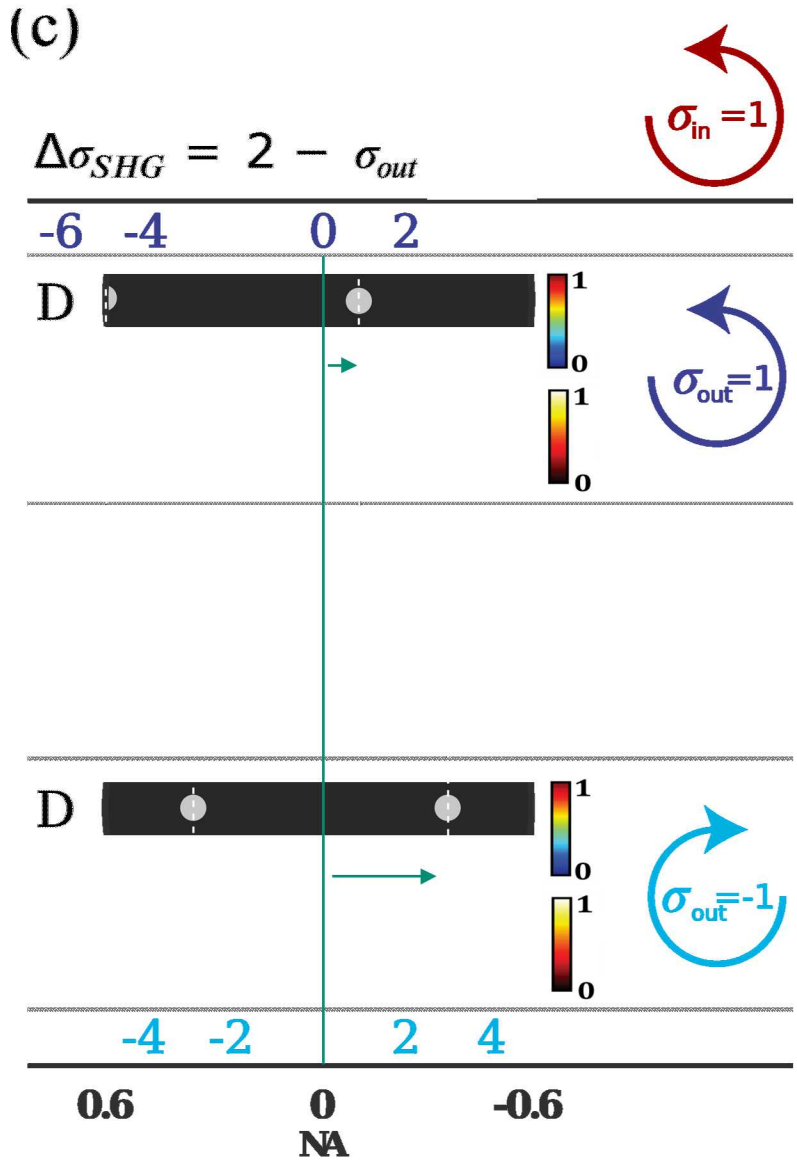
So the grating equation becomes

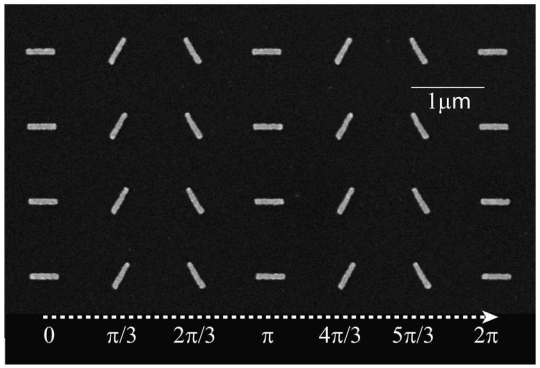
$$k_x = -(6p - \Delta\sigma_{NL})\frac{\pi}{3a}$$

Diffraction orders are shifted by integer multiples of $\pi/3a$

PB phase : Gennaro et al. ACS Photonics 2019, 6, 9, 2335-2341

SHG diffraction order

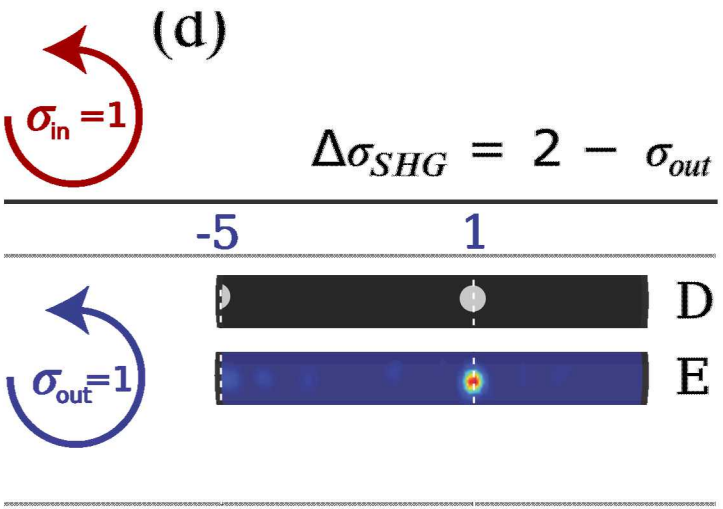


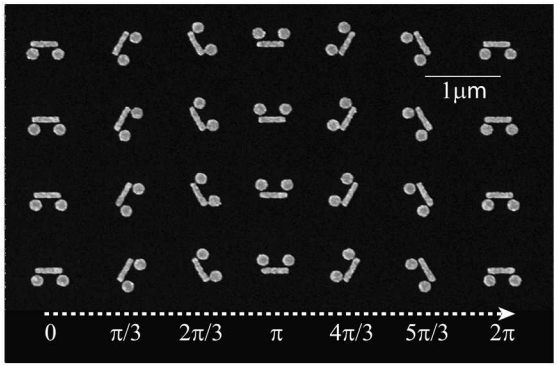


Nonlinear

SHG : $\psi^{SHG} = (2\sigma_{in} - \sigma_{out})\phi$

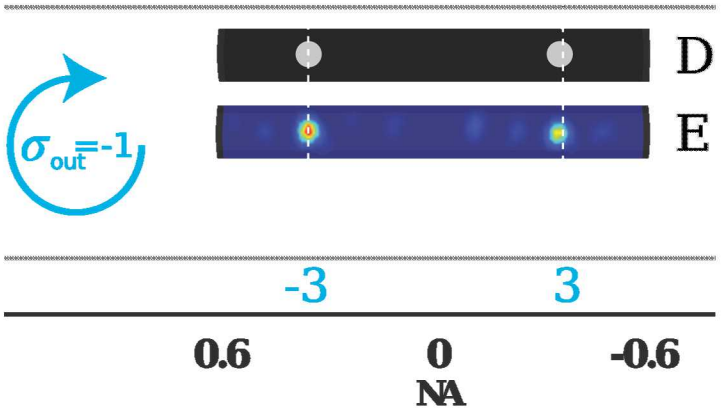
SHG diffraction order

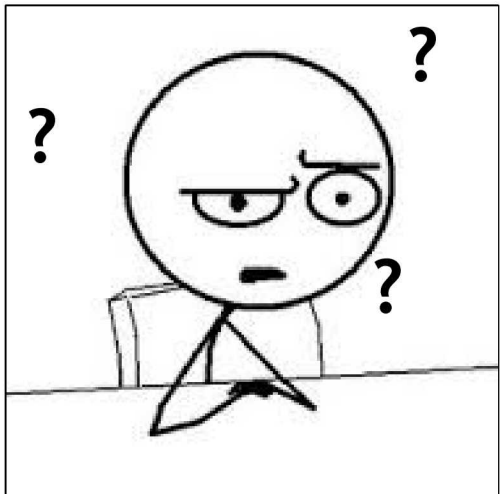




Nonlinear

SHG : $\psi^{SHG} = (2\sigma_{in} - \sigma_{out})\phi$





Grating equation with higher order modes

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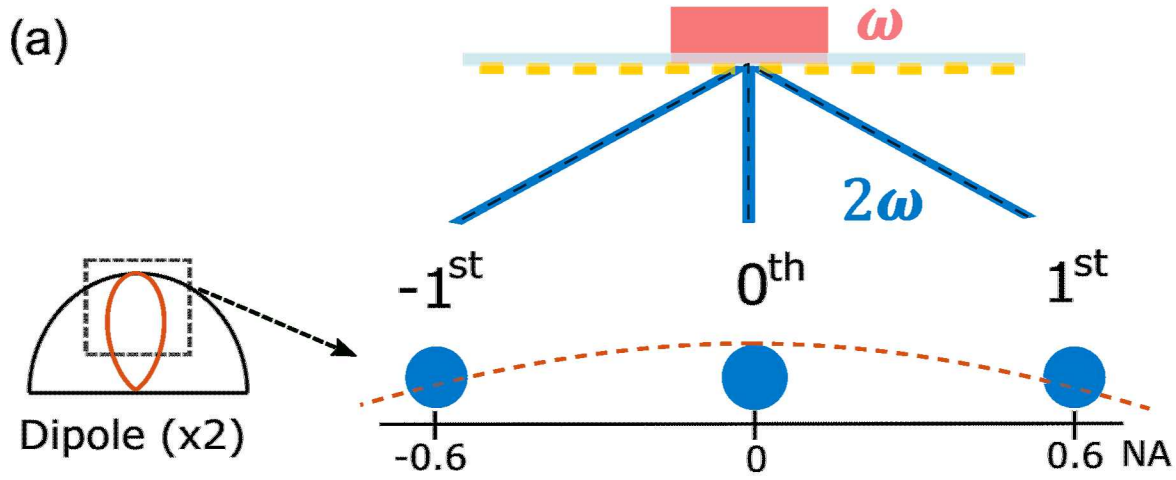

For the detailed calculation, please refer to our manuscript

PB phase : Gennaro et al. ACS Photonics 2019, 6, 9, 2335-2341

SHG diffraction order

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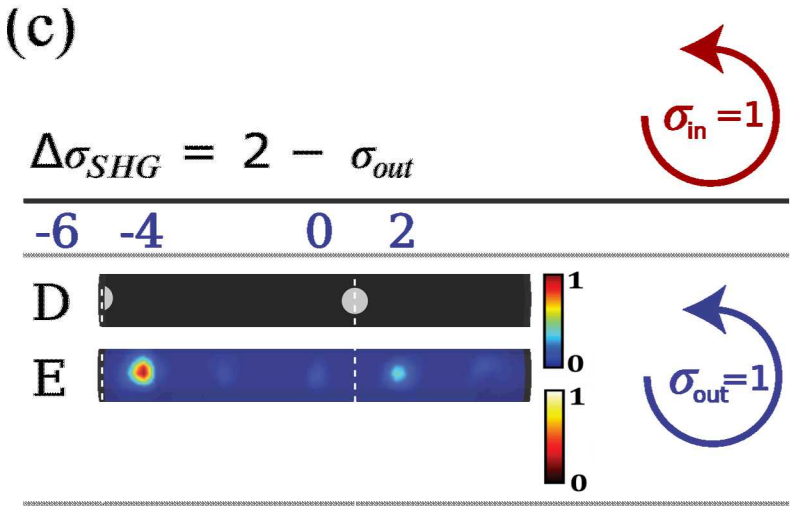
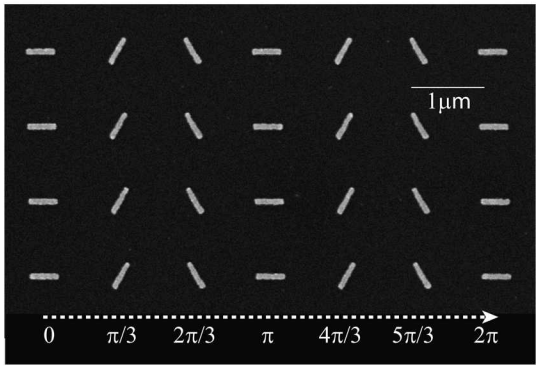


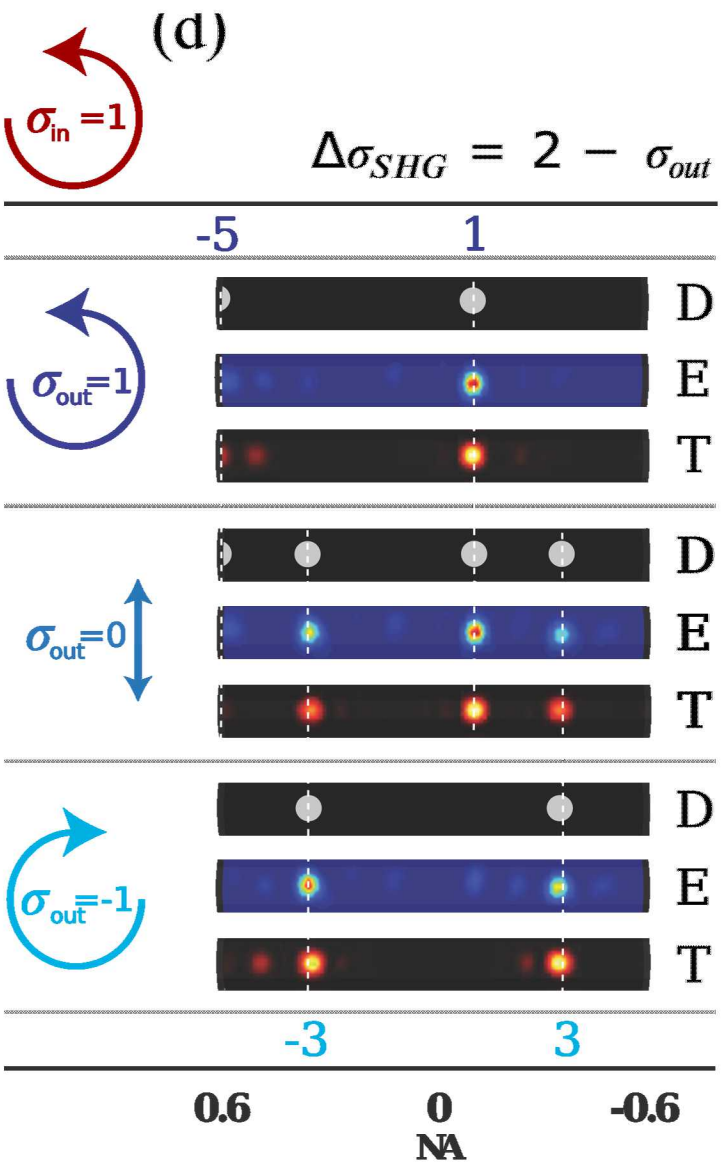


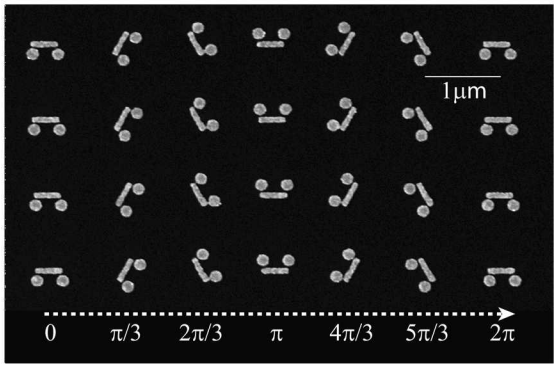
Nonlinear

SHG : $\psi^{SHG} = (2\sigma_{in} - \sigma_{out} \mp 1)\phi$

PB phase : Gennaro et al. ACS Photonics 2019, 6, 9, 2335-2341

SHG Diffraction order





Nonlinear

SHG : $\psi^{SHG} = (2\sigma_{in} - \sigma_{out})\phi$

Dipole – like emission in PB phase metasurface

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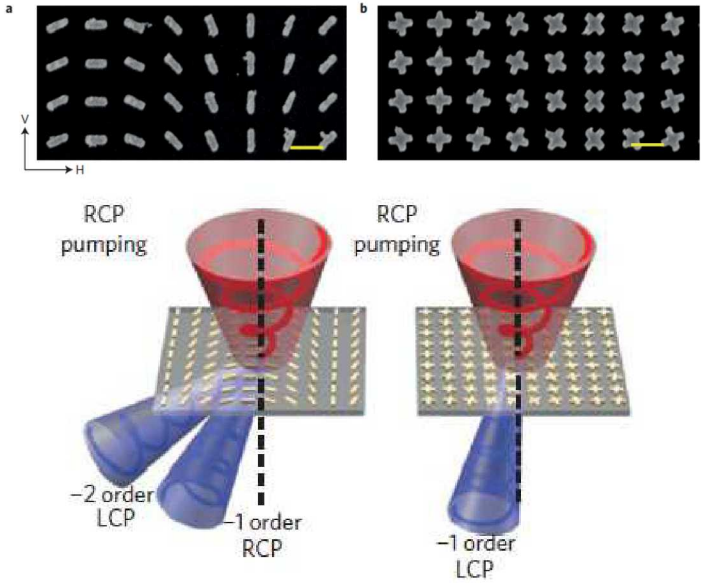
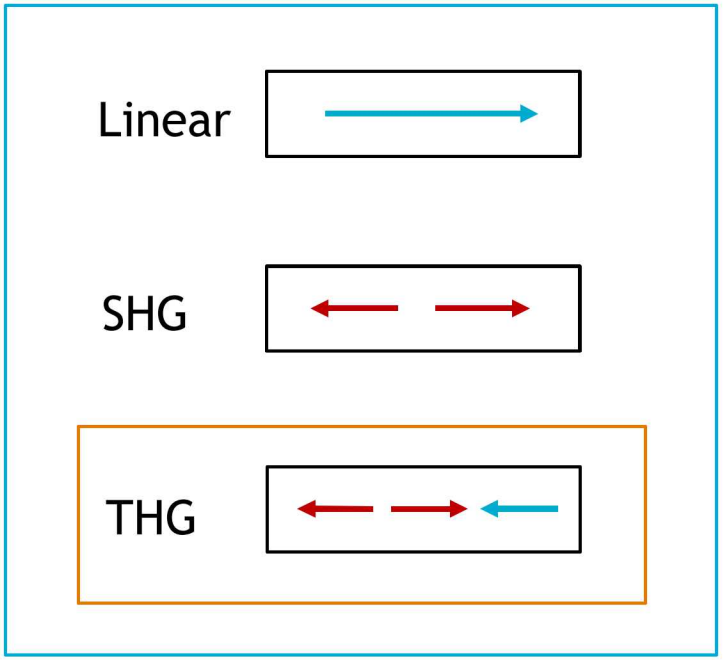


Guixin Li et al. Nature Materials. Vol 14, 607–612 (2015)

Mode of a gold bar



- THG emission from the PB metasurface is mainly dipole – like.

FWM Diffraction order

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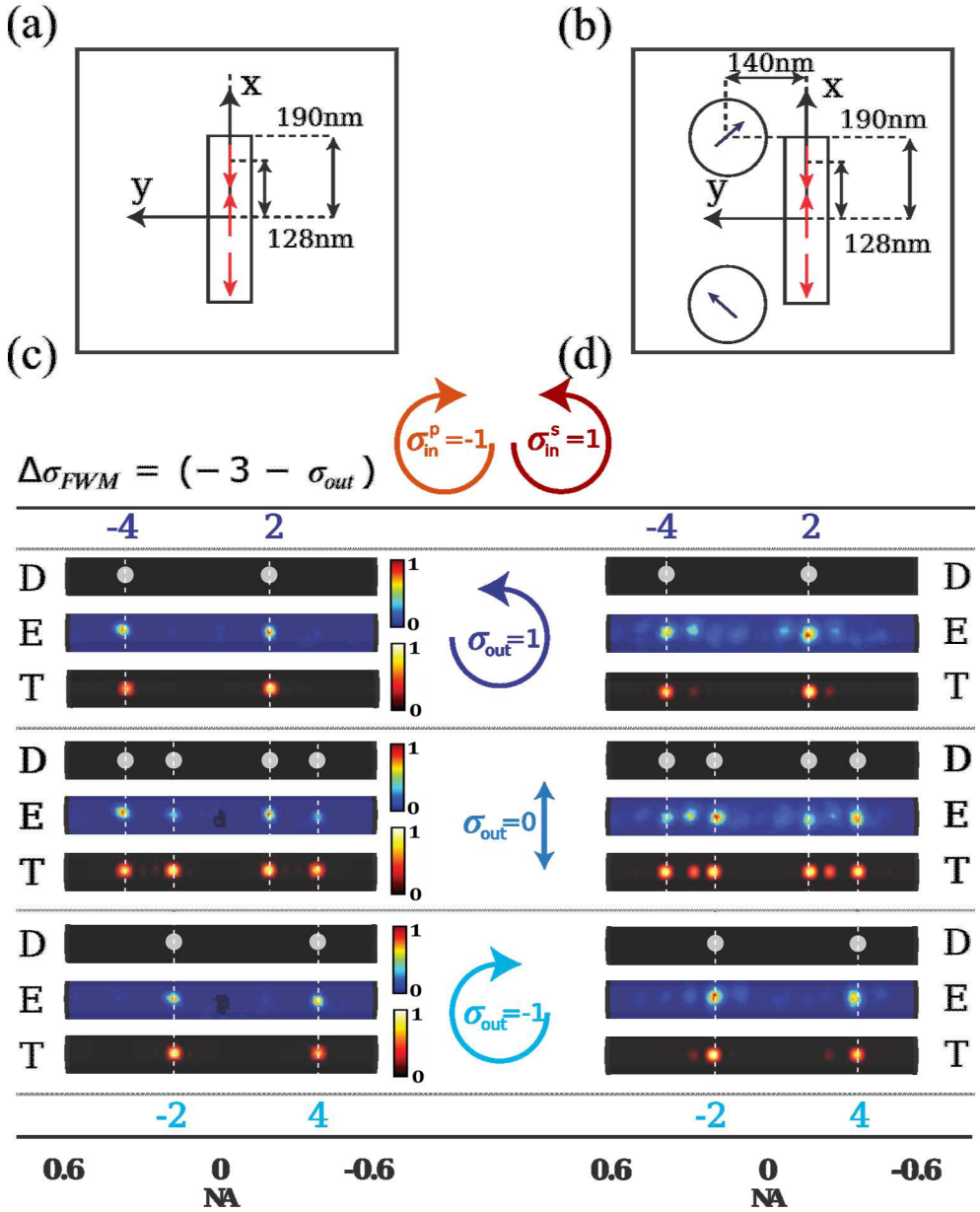


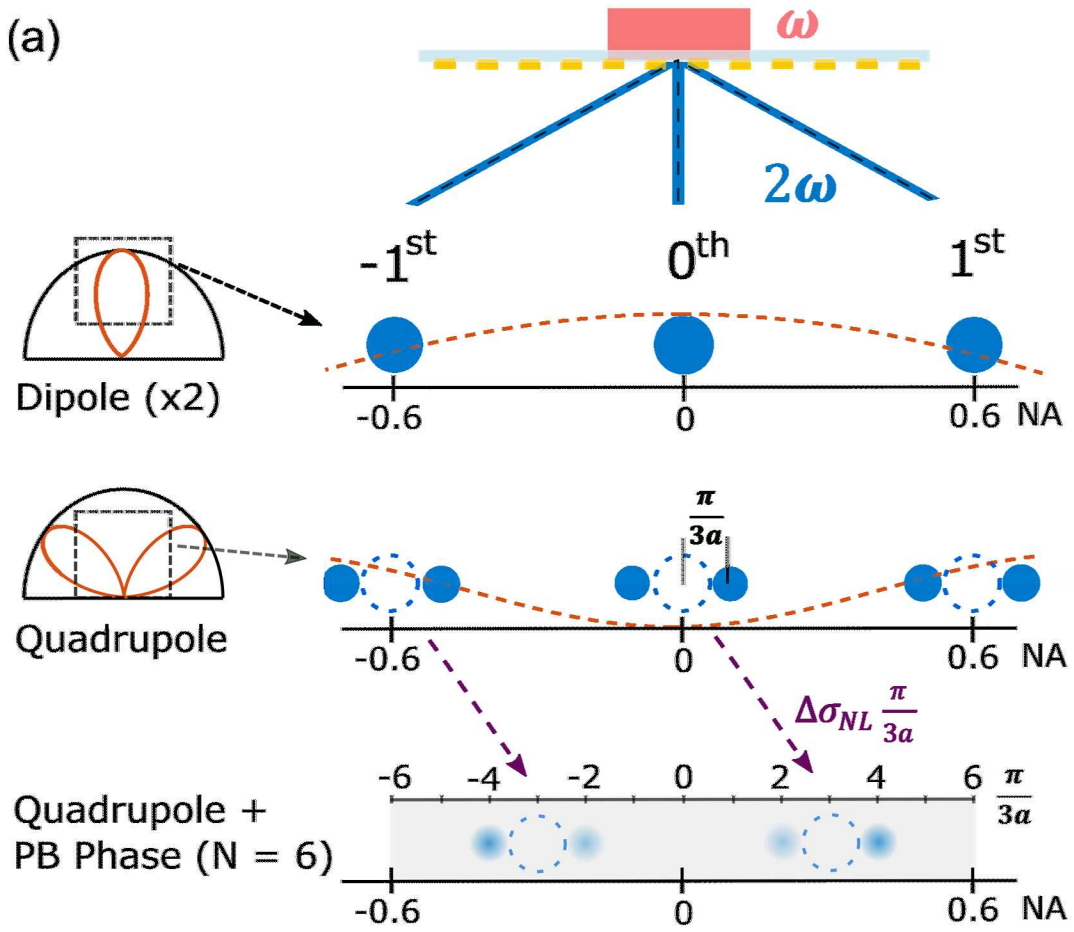
Nonlinear

FWM : $\psi^{FWM} = (2\sigma_{in}^{1} - 1\sigma_{in}^{2} - \sigma_{out})\phi$

PB phase : Gennaro et al. ACS Photonics 2019, 6, 9, 2335-2341

Li. G. et al. Laser Photon. Rev. 2018, 12, 1800034

Conclusion



SHG : Gennaro et al. Nano Lett. 2016, 16, 8, 5278-5285

FWM : Gennaro et al. *ACS Photonics* 2018, 5, 8, 3166-3171

PB phase : Gennaro et al. ACS Photonics 2019, 6, 9, 2335-2341

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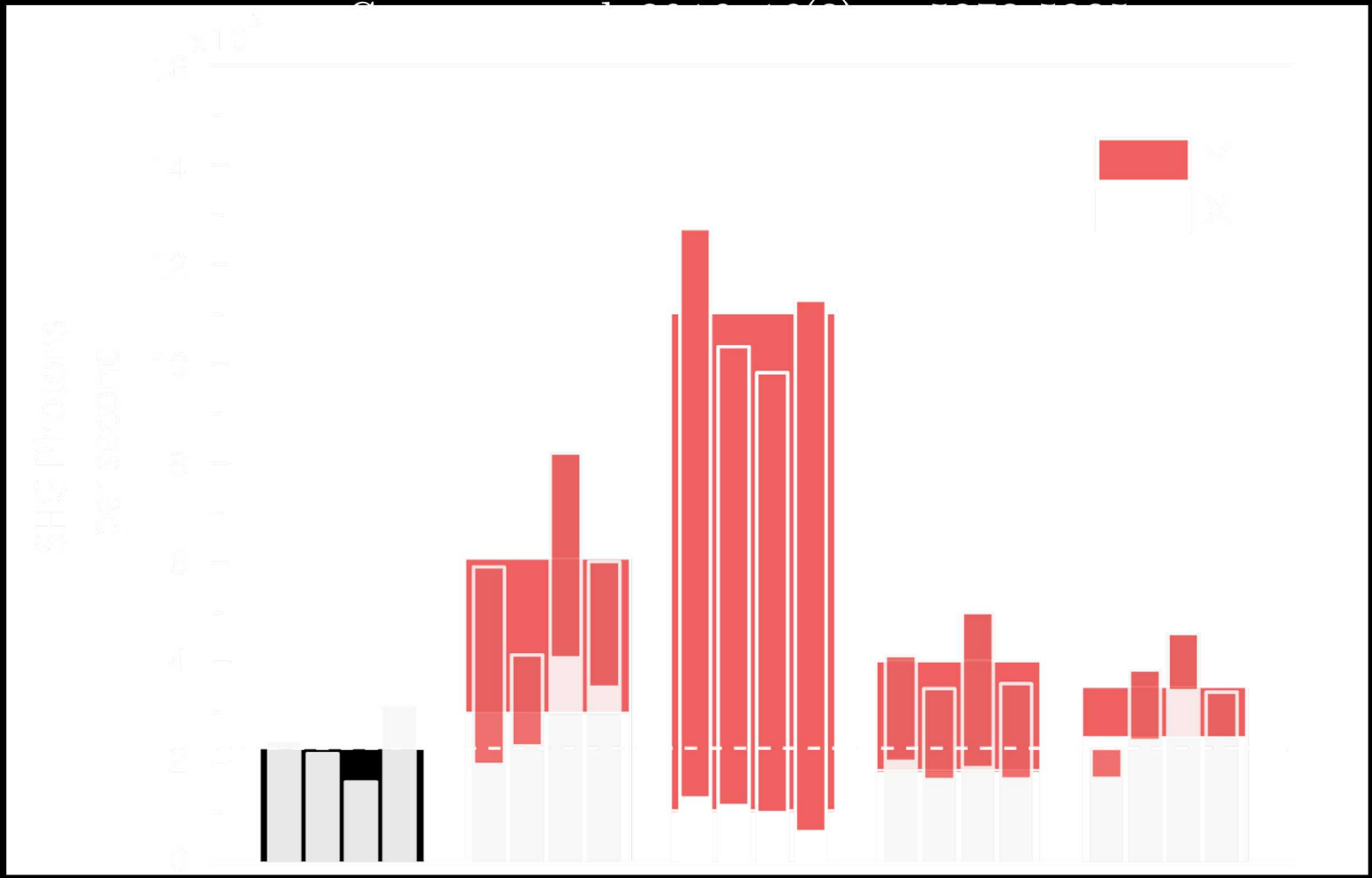
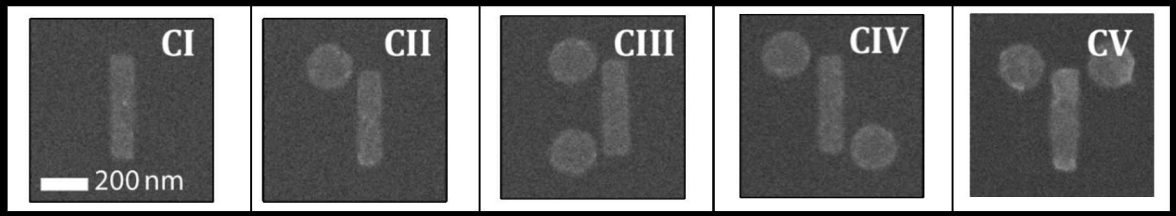
Enhancing SHG





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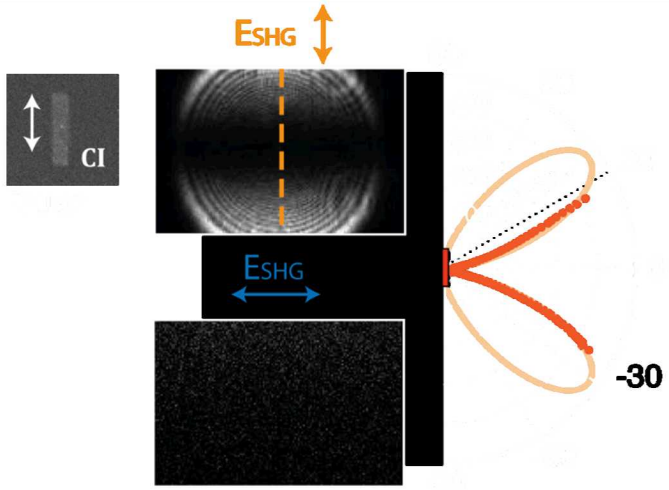

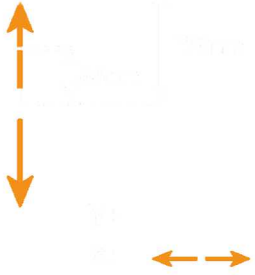

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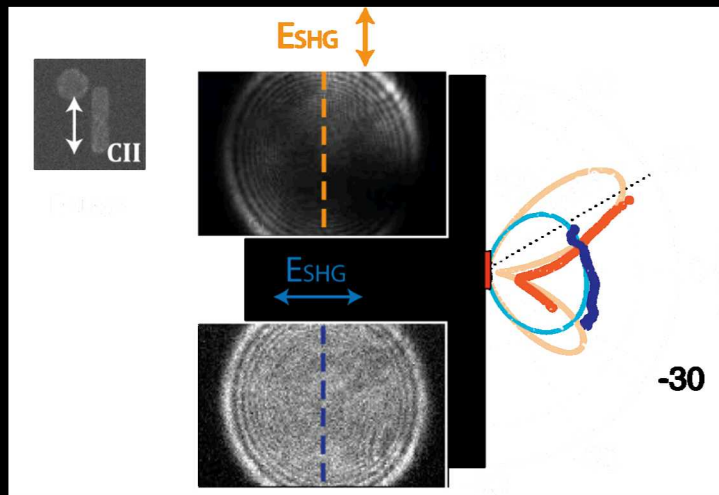
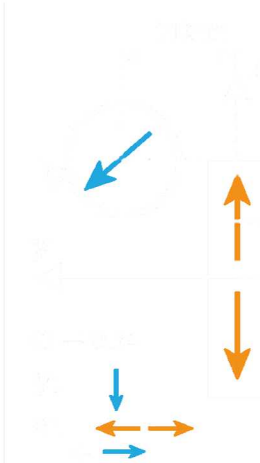
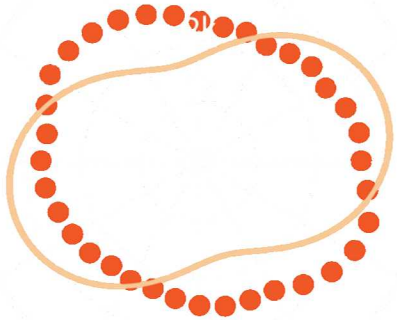
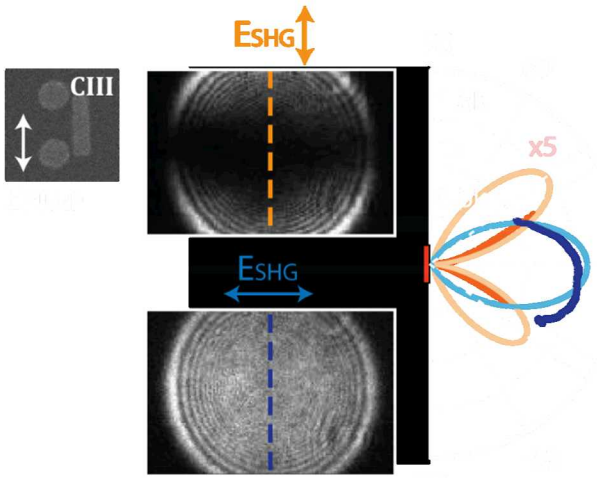
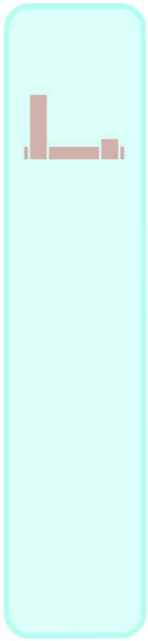


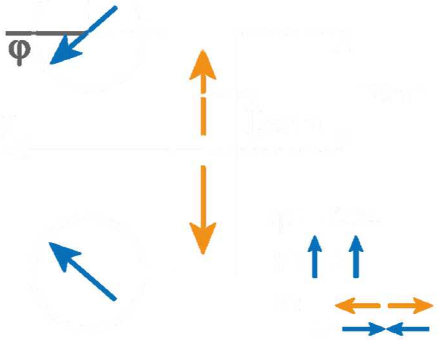


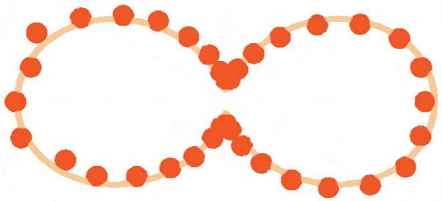


Enhancing SHG

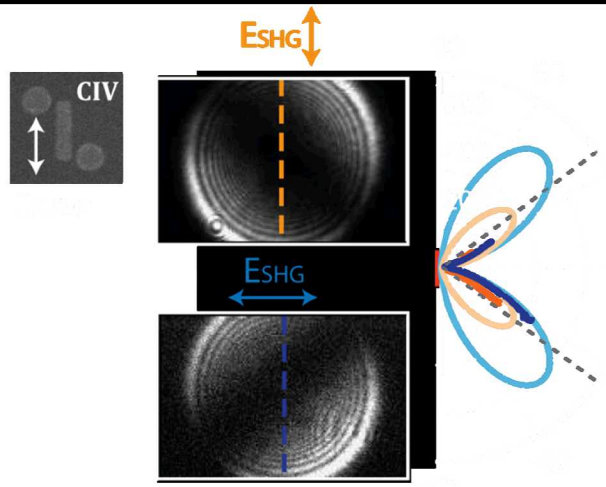


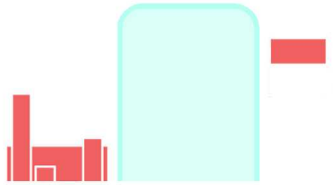


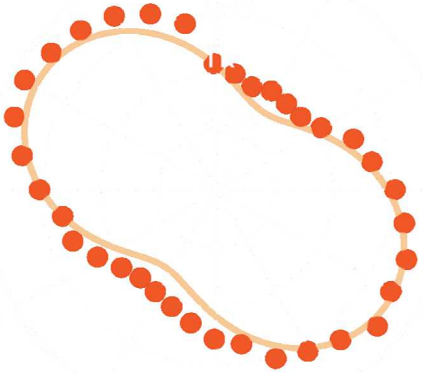


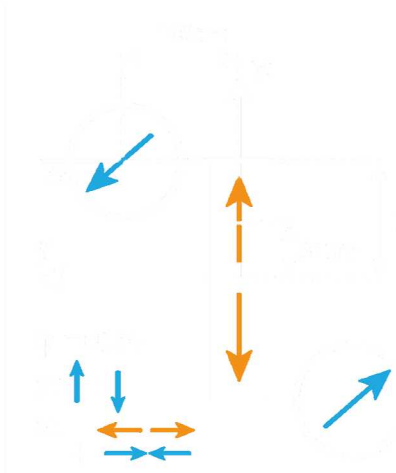


Enhancing SHG

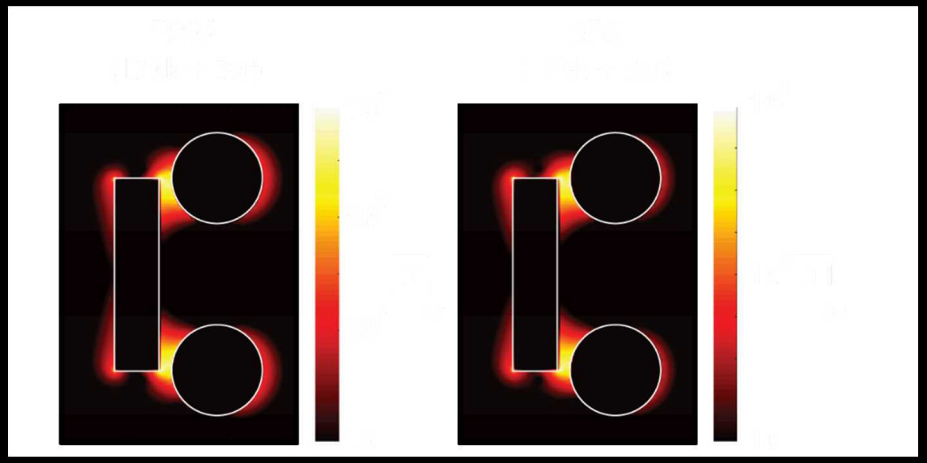


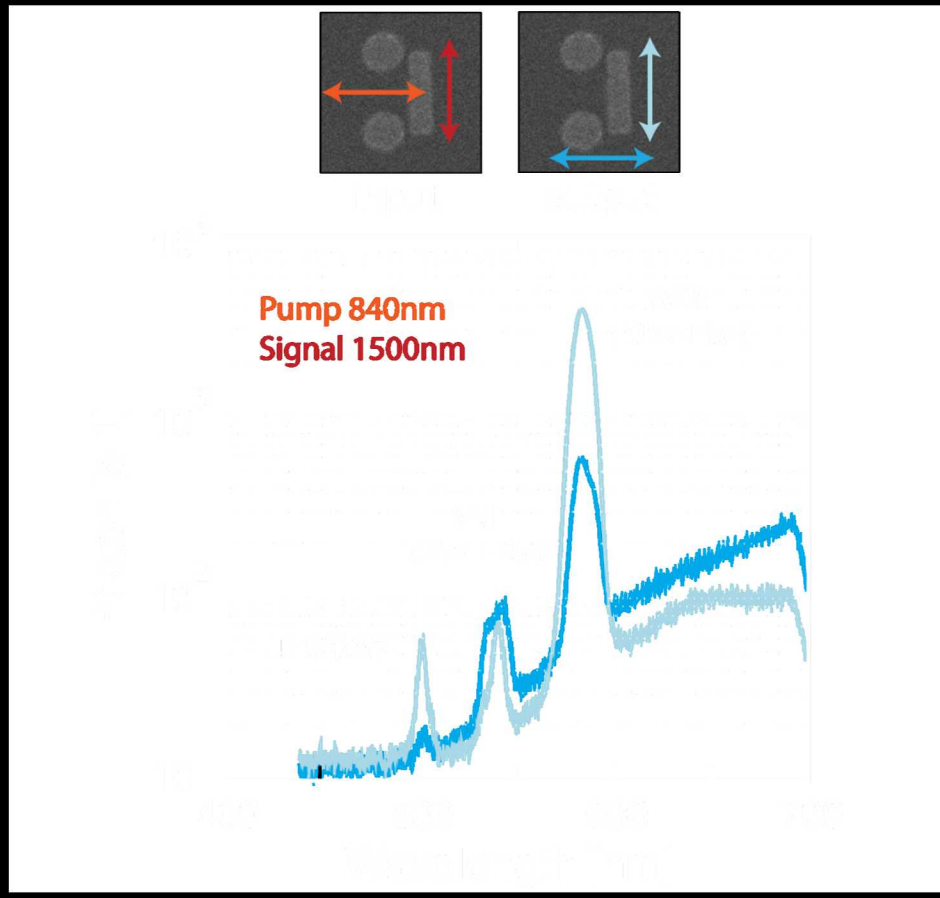






Multi Harmonic Antenna



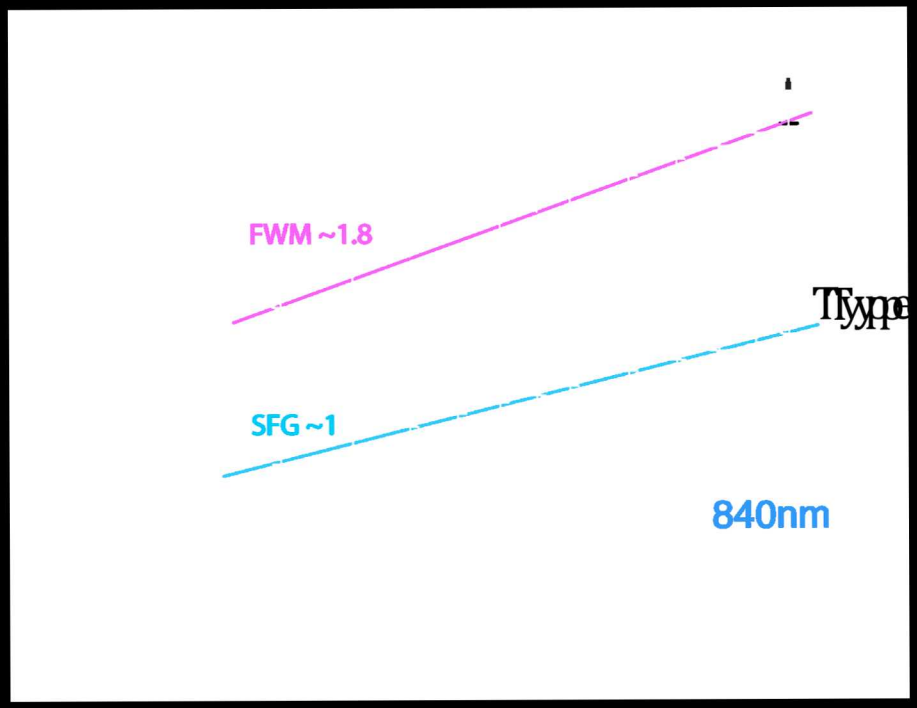


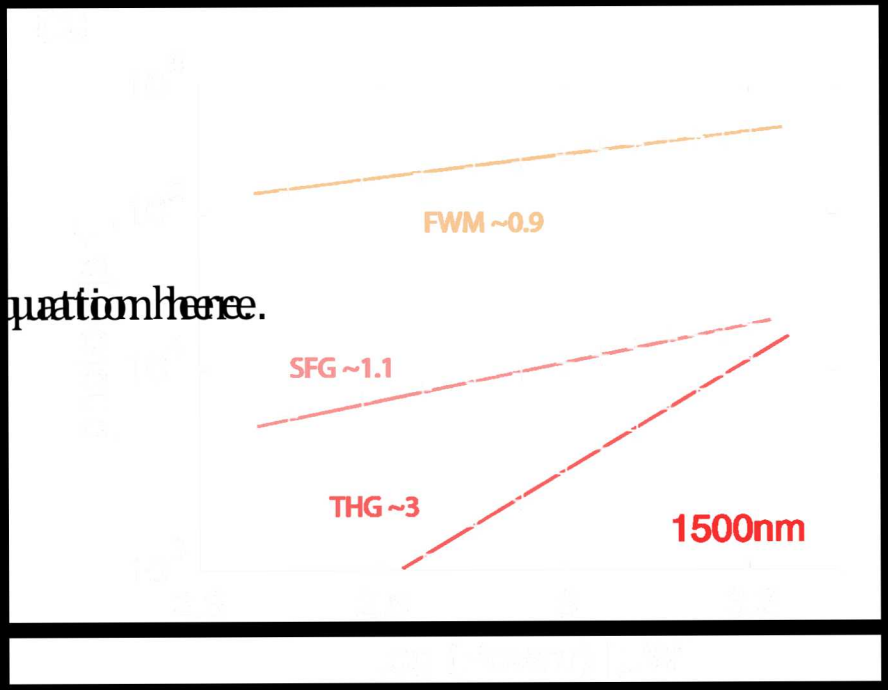
Gennaro et al. 2018, 5 (8). pp 3166–3171

Multi Harmonic Antenna

$$P_{SFG} \propto E_1(t)E_2(t)$$

$$P_{FWM} \propto E_1^2(t)E_2^*(t)$$





Gennaro et al. 2018, 5 (8). pp 3166–3171