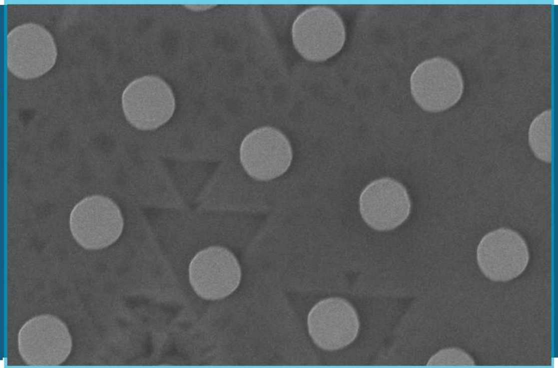
SAND2019-5033C

Tailoring Second Harmonic Diffraction in GaAs Metasurfaces via Crystal Orientation



Polina Vabishchevich [1,2], A. Vaskin[3], S. Addamane[4], S. Liu[1,2], A. P. Sharma[4], G. Balakrishnan[4], J. L. Reno[1,2], G. A. Keeler[1], M. B. Sinclair[1], I. Staude[3], Igal Brener[1,2]

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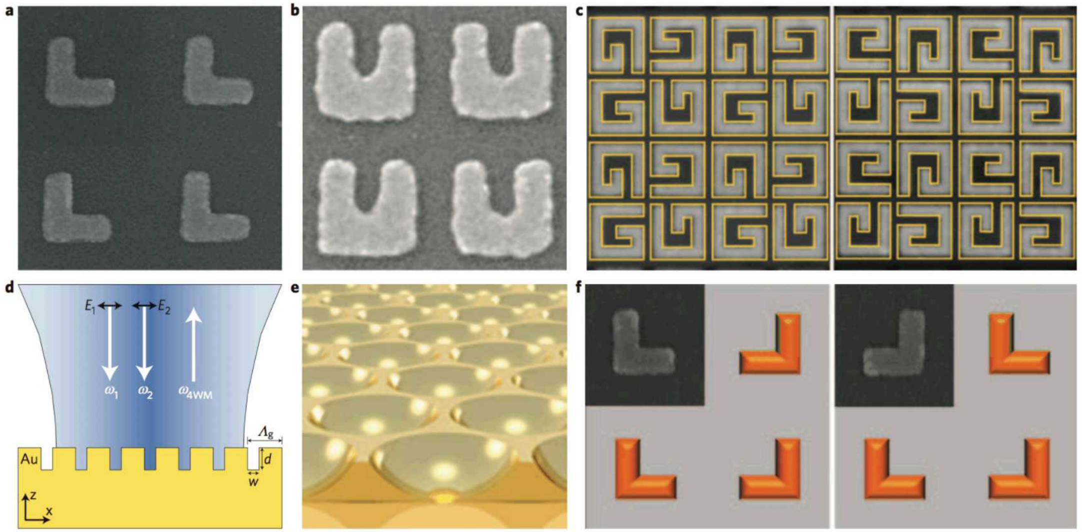
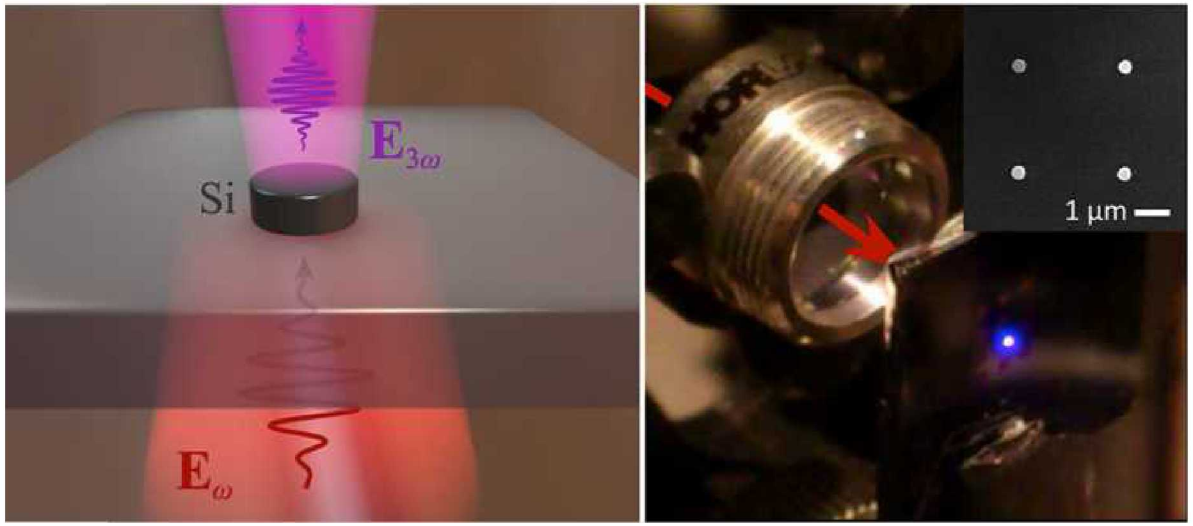
Nonlinear Photonic Metasurfaces



Kauranen, M., and Zayats, A. V. *Nature Photonics*, *6*(11), 737, **(2012)**



M .R. Shcherbakov, et. al. *Nano Letters* **14,** 11, 6488–6492, 2014

- Surface/Local Plasmon resonances
- Mie resonances

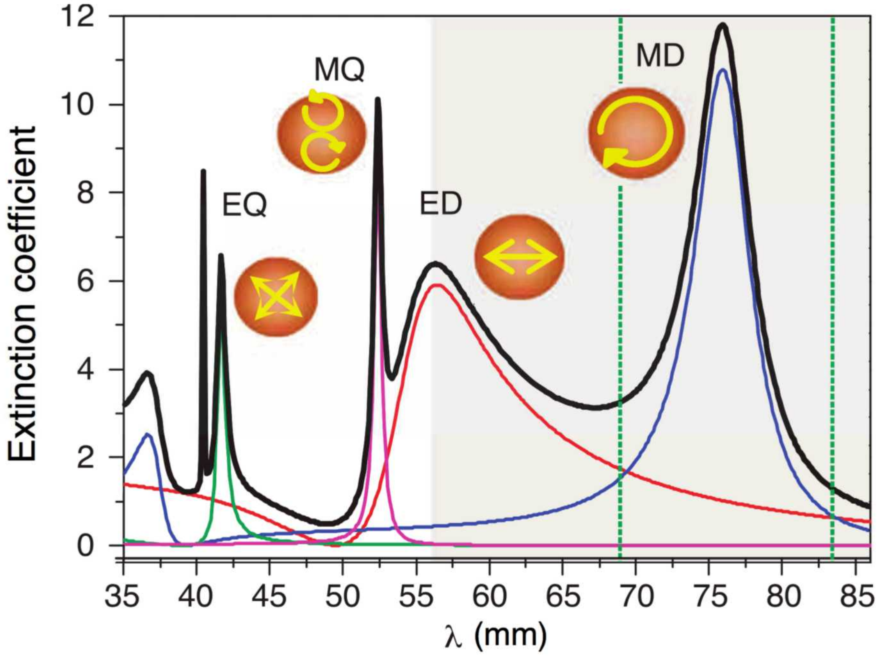
Resonant enhancement of EM field

Dimensions < wavelength

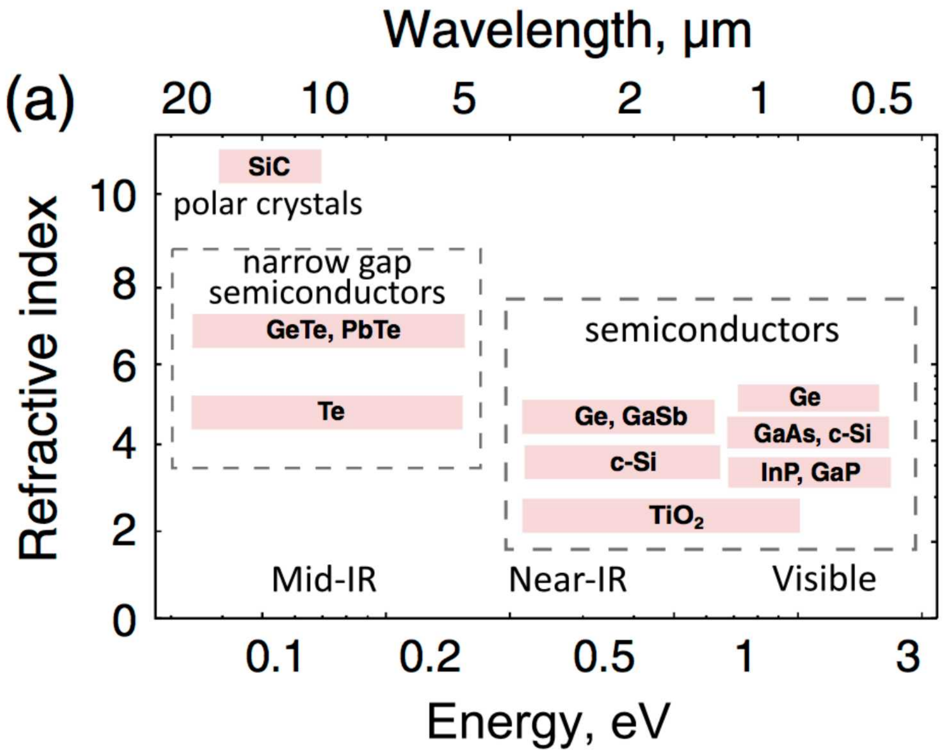
Relaxed phase matching conditions

Mie resonances in dielectric spheres

Mie resonances in Dielectric spheres



Geffrin, J.-M., et al. *Nat. Commun.* 3, 1171, **2012**



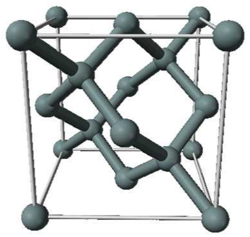
Baranov, D.G., et al. *Optica* 4.7, 814-825, **2017**

Mie resonances
- Low losses
- Much larger mode volume
- High nonlinear coefficient materials (GaAs: ~200pm/V)

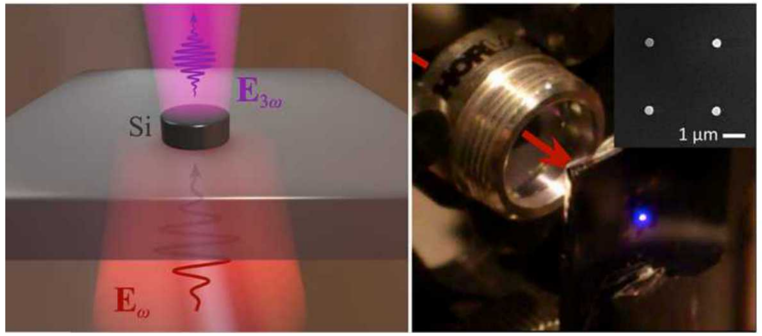
Nonlinear dielectric metasurfaces

centrosymmetric

Si
Ge

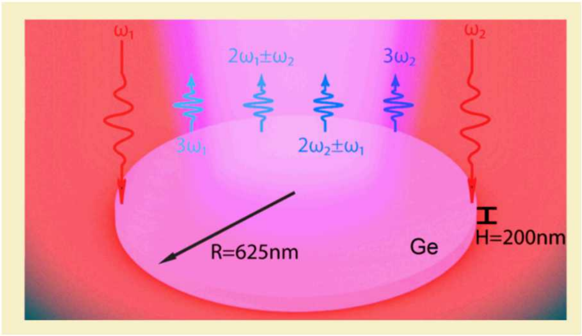


Third Harmonic Generation



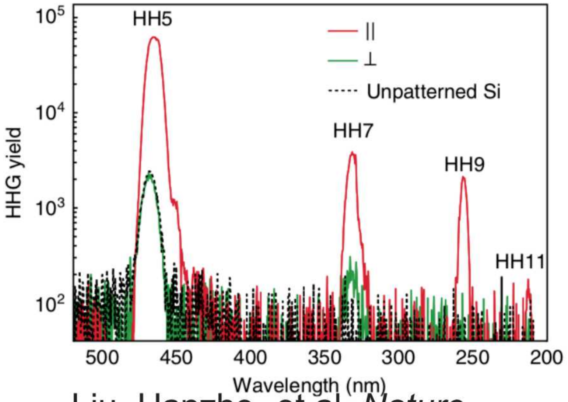
M .R. Shcherbakov, et. al. *Nano Letters* **14,** 11, 6488–6492, **2014**

Four-Wave Mixing



Grinblat, G., et al, ACS Photonics 4, 2144-2149, **2017**

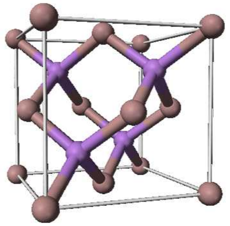
High-Harmonic Generation



Liu, Hanzhe, et al. *Nature Physics* 14.10,1006, **2018**

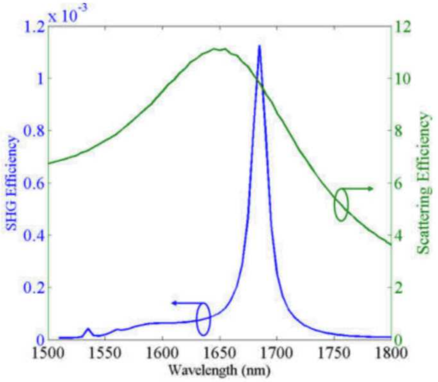
Non-centrosymmetric

GaAs
AlGaAs

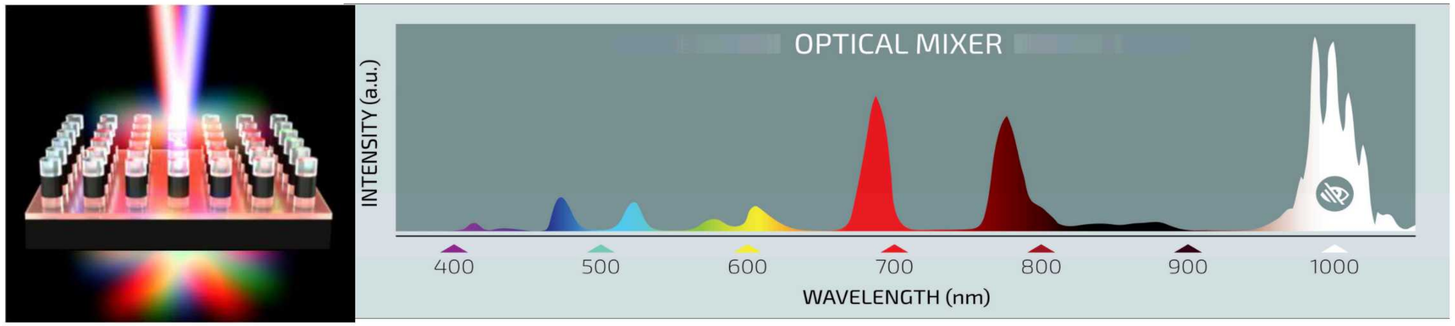


https://www.wikipedia.org

Second Harmonic Generation (10^{-8} W/W^2)
Nonlinear Frequency Mixing

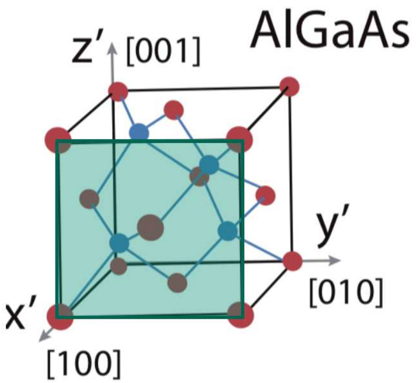


L. Carletti et al., *ACS Photonics*, *3*(8), 1500-1507, **2016**



Liu, Sheng, et al. *Nature communications* 9.1, 2507, **2018**

GaAs (100) lattice plane

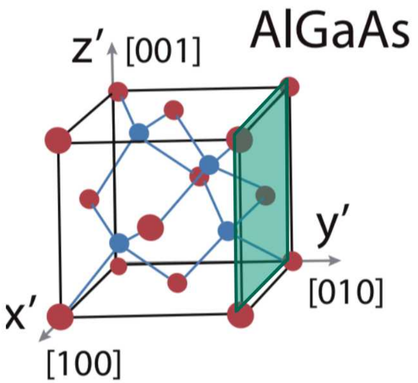


$$\begin{pmatrix} P_x(2\omega) \\ P_y(2\omega) \\ P_z(2\omega) \end{pmatrix} = 2\varepsilon_0 d_{eff} \begin{pmatrix} E_x(\omega)^2 \\ E_y(\omega)^2 \\ E_z(\omega)^2 \\ 2E_y(\omega)\cdot E_z(\omega) \\ 2E_x(\omega)\cdot E_z(\omega) \\ 2E_y(\omega)\cdot E_x(\omega) \end{pmatrix}$$

$$d_{eff} = \begin{pmatrix} 0 & 0 & 0 & d_{41} & 0 & 0 \\ 0 & 0 & 0 & 0 & d_{41} & 0 \\ 0 & 0 & 0 & 0 & 0 & d_{41} \end{pmatrix}$$

Absence of SHG in normal direction

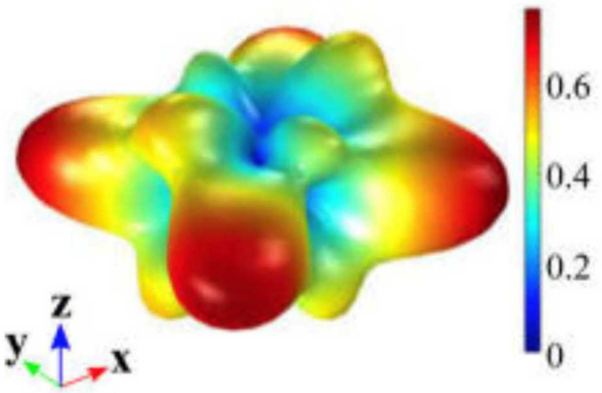
GaAs (100) single disk and metasurface emission patterns

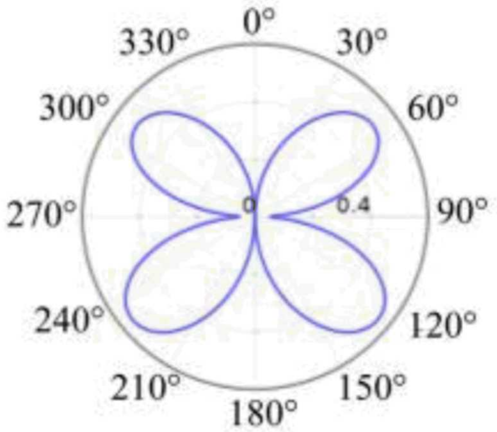


$$d_{eff} = \begin{pmatrix} 0 & 0 & 0 & d_{41} & 0 & 0 \\ 0 & 0 & 0 & 0 & d_{41} & 0 \\ 0 & 0 & 0 & 0 & 0 & d_{41} \end{pmatrix}$$

→ Absence of SHG in normal direction

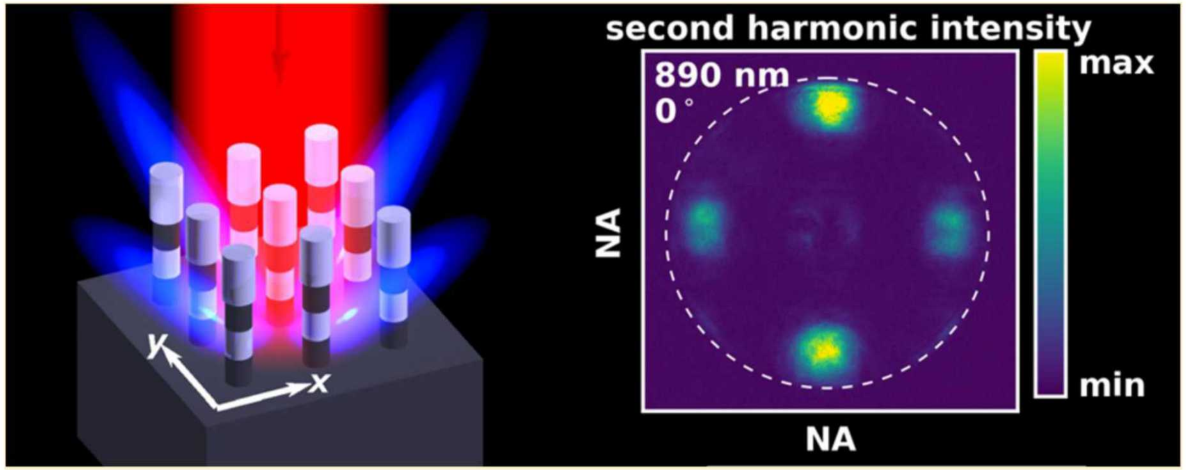
SHG radiation pattern in AlGaAs (100) nanodisks at MD resonance





L. Carletti et al., *ACS Photonics*, *3*(8), 1500-1507, **2016**

SHG diffraction in the GaAs (100) metasurface

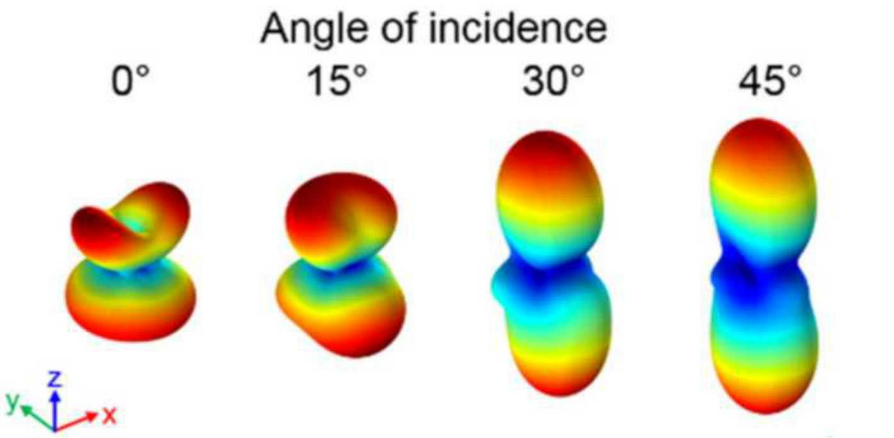


Löchner, F. J., *ACS Photonics*, *5*(5), 1786-1793, **2018**

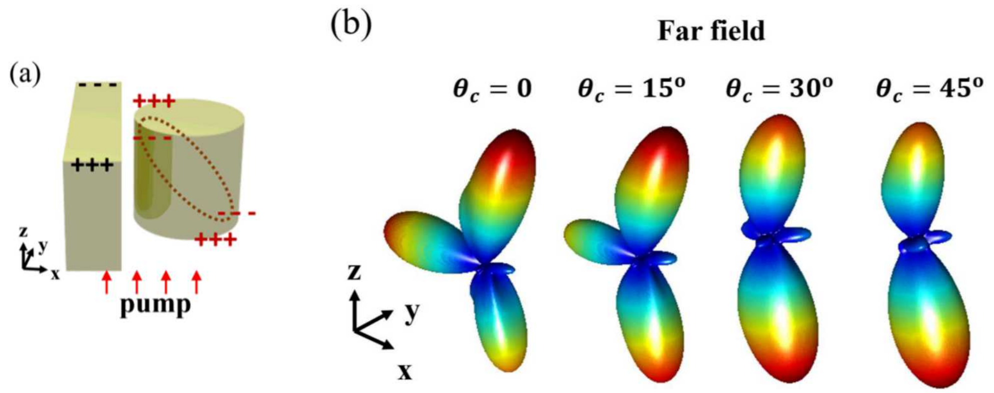
Absence of the zeroth-order

Tailoring of SHG in normal direction

Use of non-normal incidence

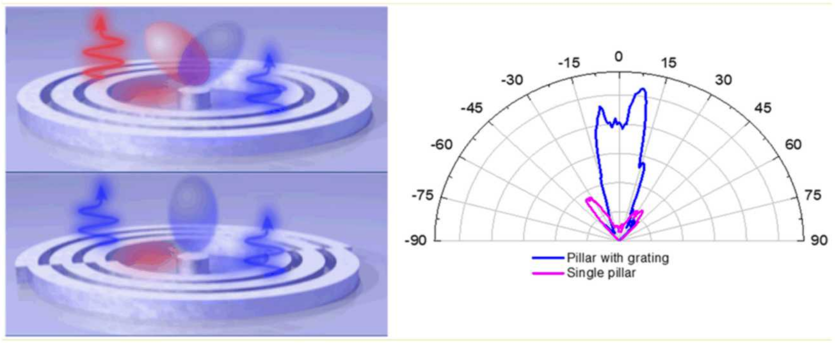


Carletti, L., *Nanotechnology*, *28*(11), 114005, **2017**

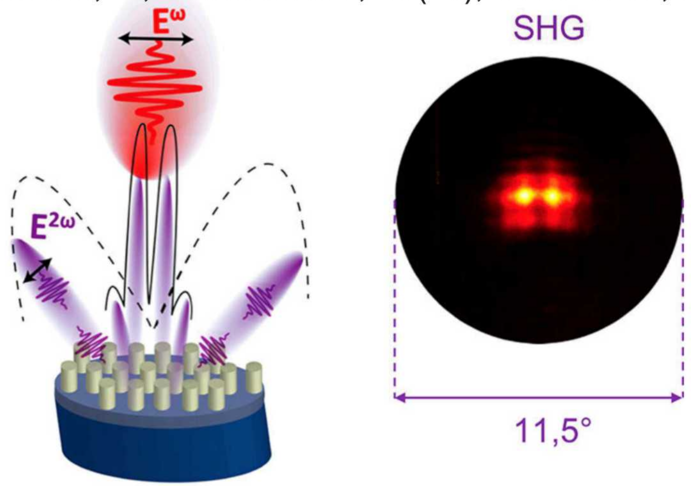


Xu, L., Rahmani, In *Photonics* (Vol. 5, No. 3, p. 29). Multidisciplinary Digital Publishing Institute, **2018**

Use of additional gratings

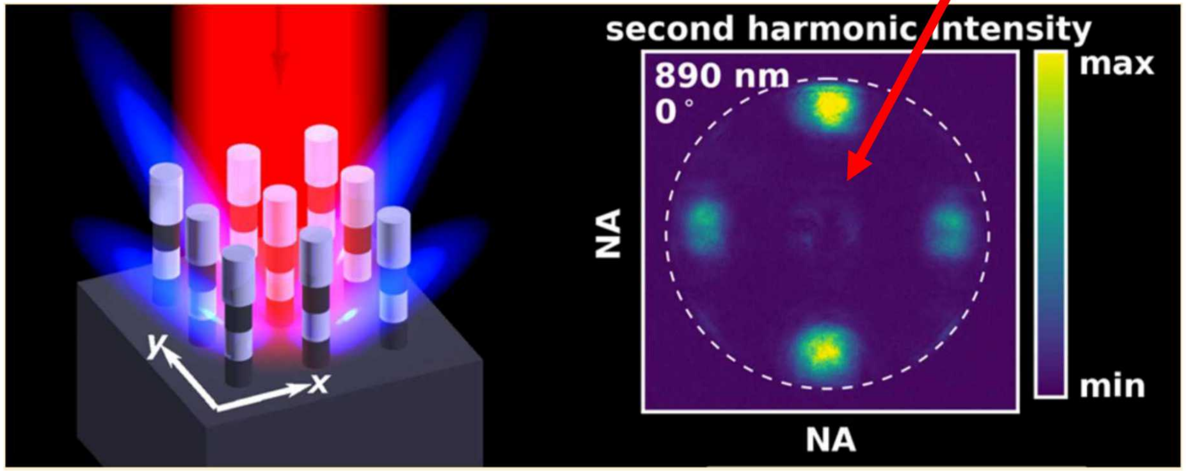


Ghirardini, L., *Nano letters*, *18*(11), 6750-6755, **2018**

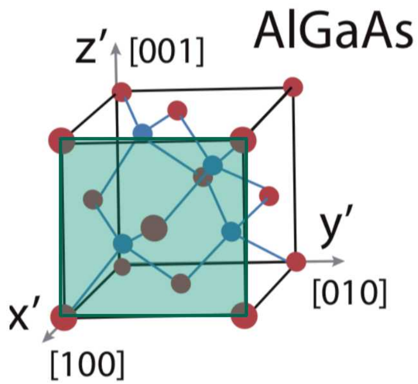


Marino, G., *ACS Photonics*, Articles ASAP **2019**

Goal: Redirection of the SHG emission to zeroth diffraction order in GaAs metasurfaces

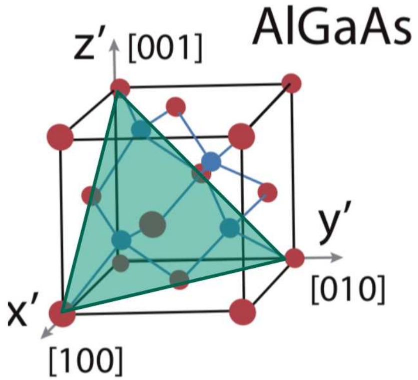


Use of (111) GaAs/AlGaAs



$$d_{eff} = \begin{pmatrix} 0 & 0 & 0 & d_{41} & 0 & 0 \\ 0 & 0 & 0 & 0 & d_{41} & 0 \\ 0 & 0 & 0 & 0 & 0 & d_{41} \end{pmatrix}$$

Absence of SHG under normal incidence



$$d_{eff} = \begin{pmatrix} -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} & 0 & 0 & -\frac{1}{\sqrt{3}} & 0 \\ 0 & 0 & 0 & -\frac{1}{\sqrt{3}} & 0 & -\frac{1}{\sqrt{6}} \\ -\frac{1}{2\sqrt{3}} & -\frac{1}{2\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 & 0 & 0 \end{pmatrix} \cdot d_{41}$$

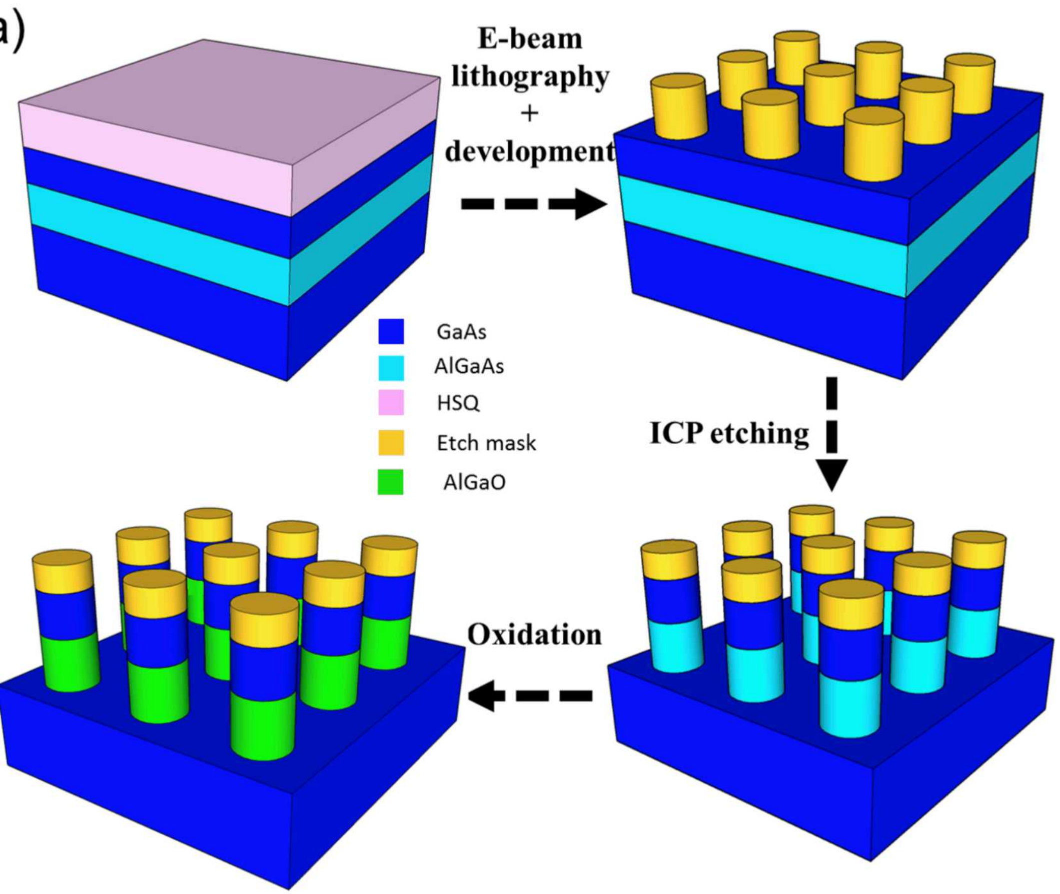
Non-zero SHG signal for (111) Lattice plane under normal incidence

$$P_x(2w) = 2\varepsilon_0 d_{eff}(-\frac{1}{\sqrt{6}})E_x(w)^2 + \frac{1}{\sqrt{6}}E_y(w)^2 - \frac{1}{\sqrt{3}}E_x(w)E_z(w)$$

$$P_y(2w) = 2\varepsilon_0 d_{eff}(-\frac{2}{\sqrt{3}})E_y(w)E_z(w) - \frac{1}{\sqrt{6}}E_x(w)E_z(w)$$

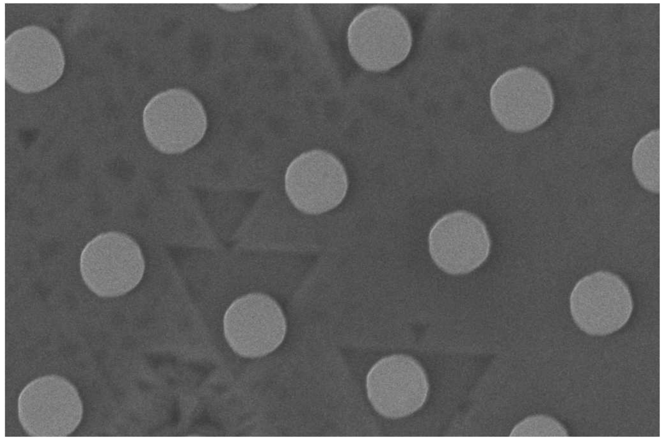
$$P_z(2w) = 2\varepsilon_0 d_{eff}(-\frac{1}{2\sqrt{3}})E_x(w)^2 - \frac{1}{2\sqrt{3}}E_y(w)^2 - \frac{1}{1\sqrt{3}}E_z^2$$

Fabrication of GaAs metasurface

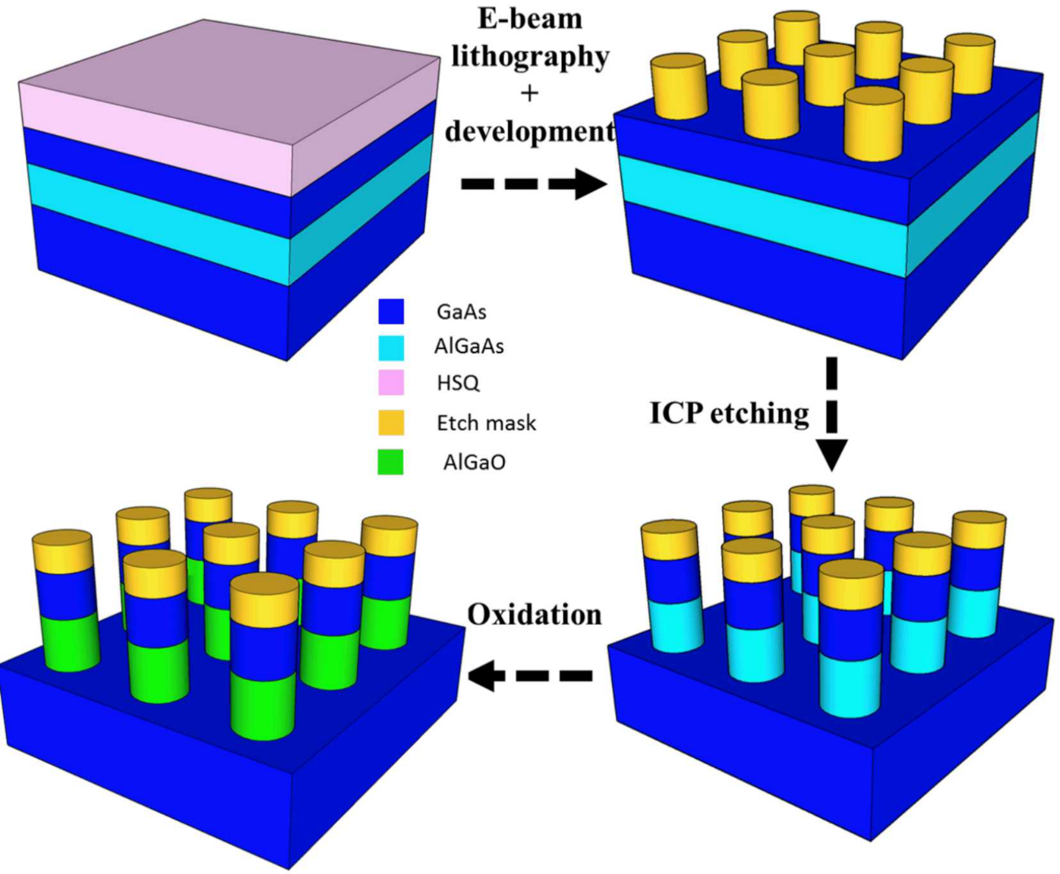


Liu, S. et. al. *Nano letters* 16.9: 5426-5432, **2016**

SiO_x – 400 nm
$Al_{0.1}Ga_{0.9}As$ – 400 nm
$(Al_xGa_{1-x})_2O_3$ – 500 nm
Diameter – 340 nm
Period – 1200 nm



Fabrication of GaAs metasurface



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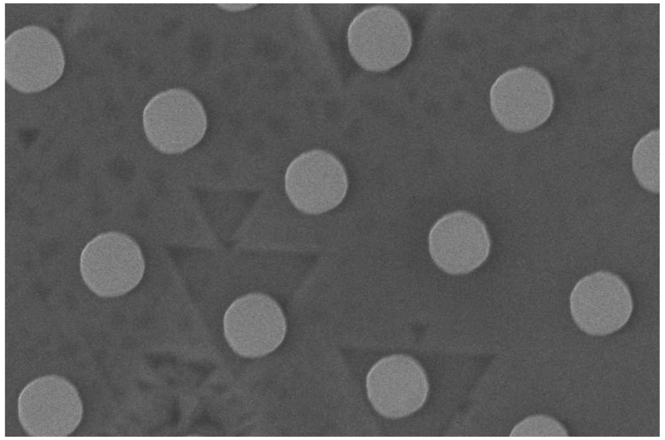
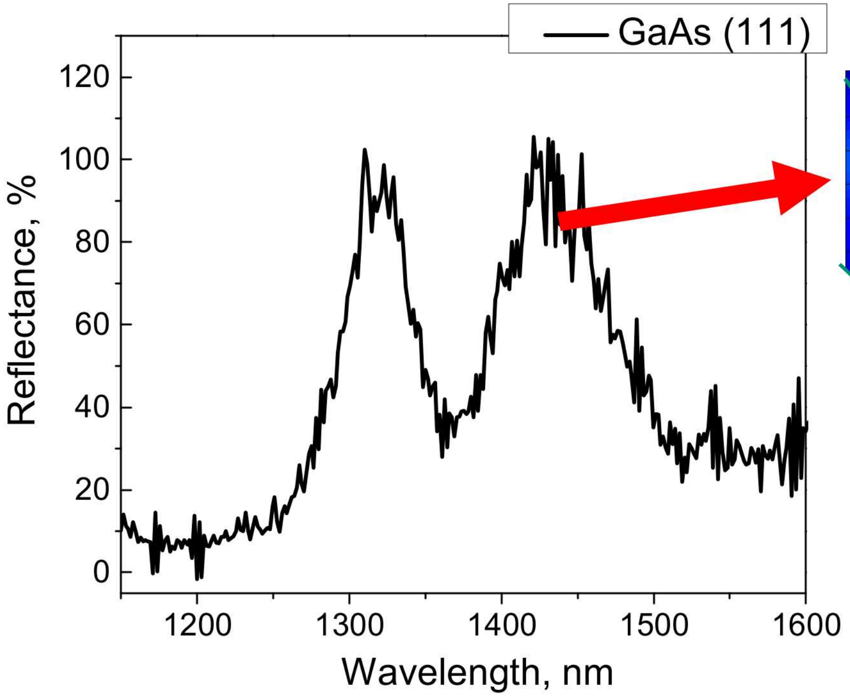
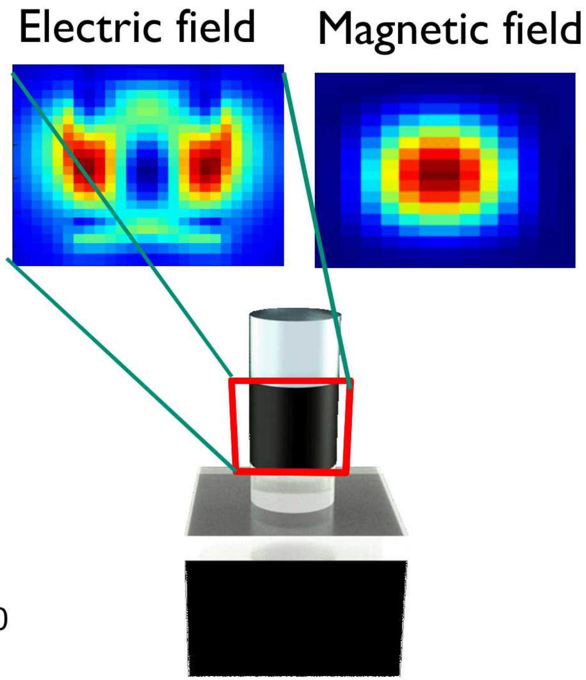
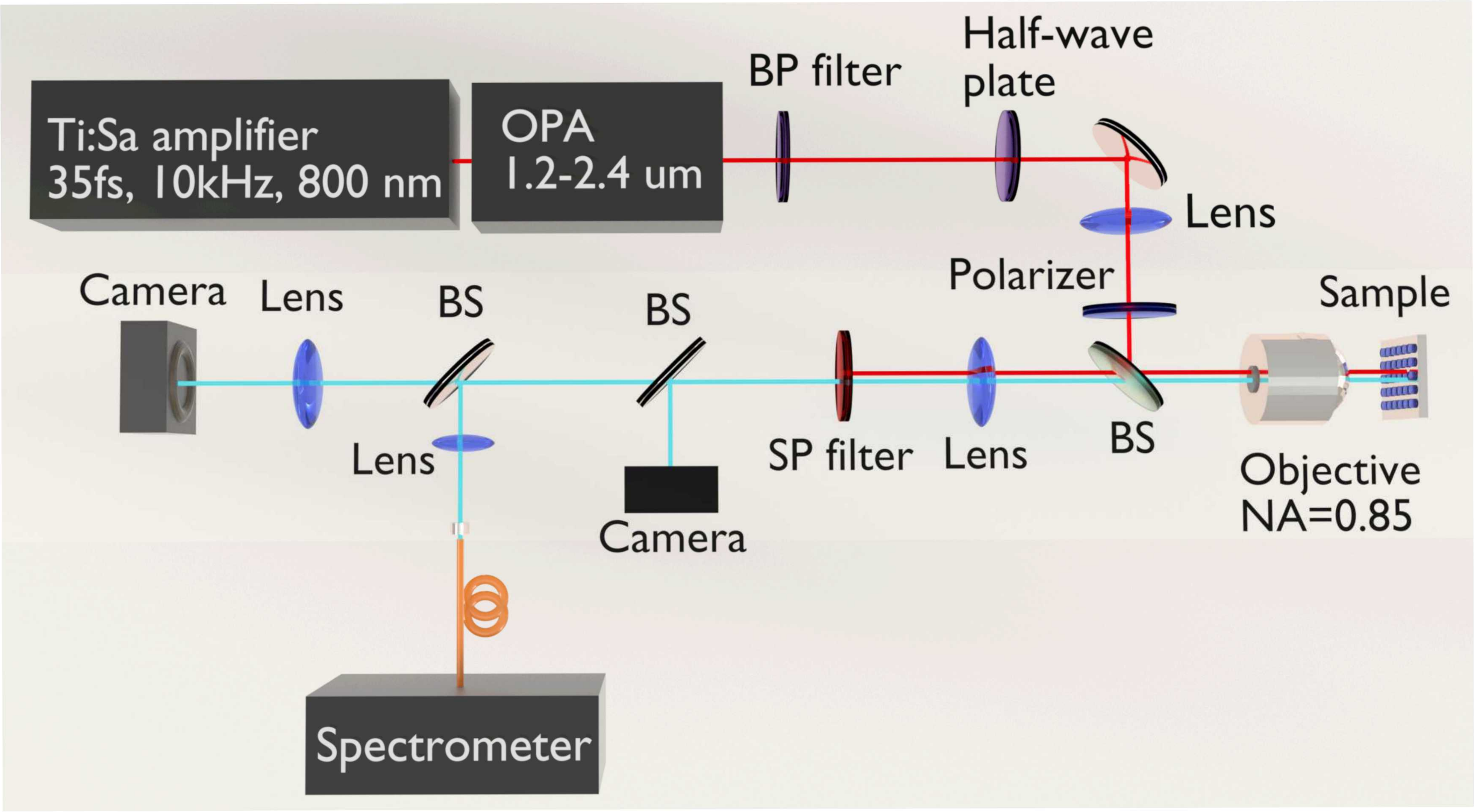


Reflectance spectrum

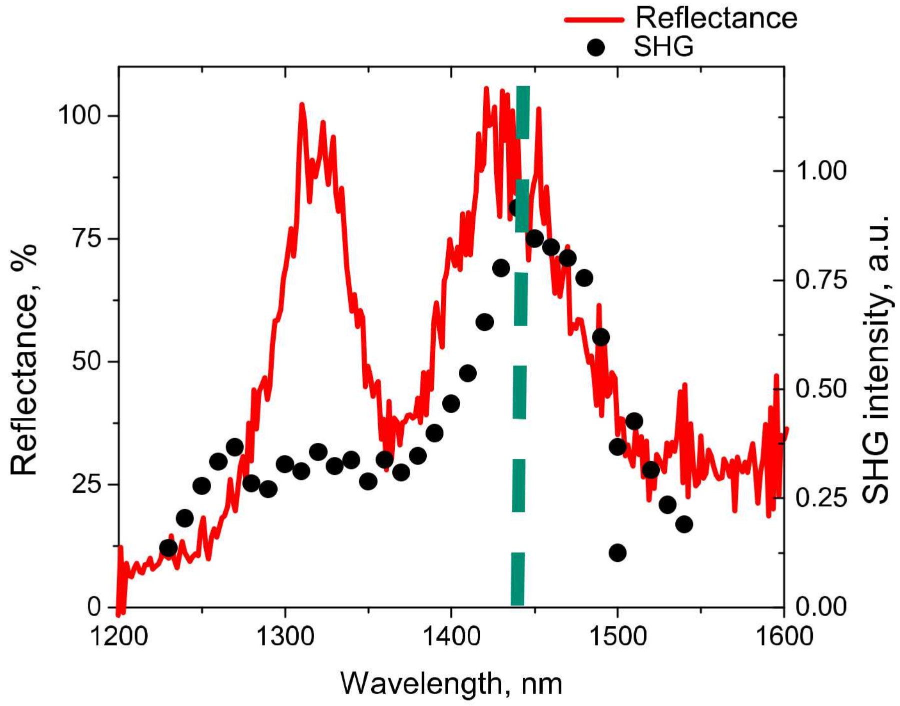




Experimental setup: Fourier-space imaging

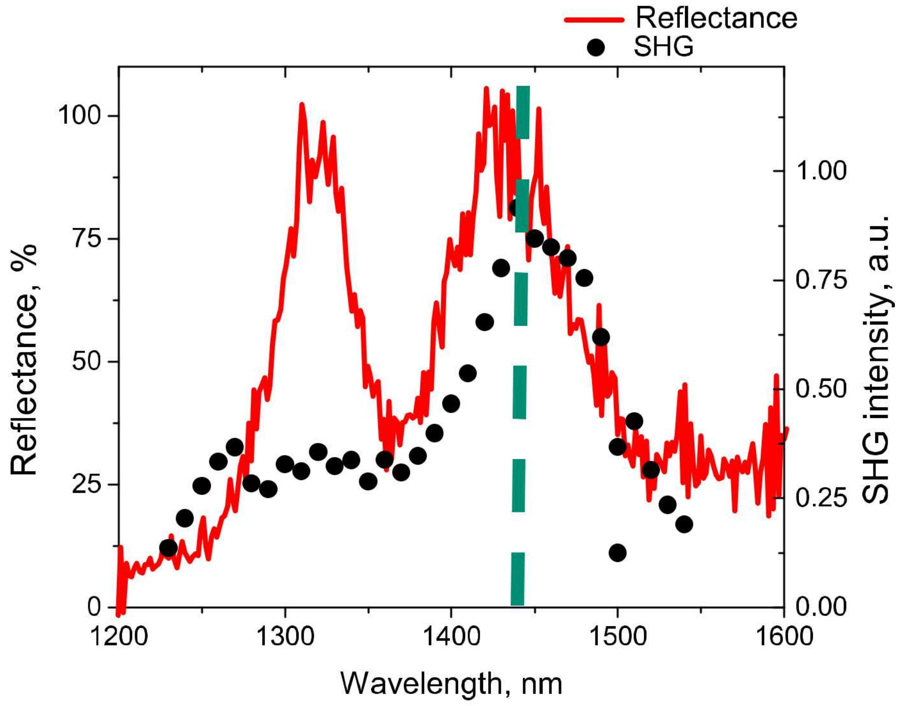


SHG in GaAs (111) metasurface

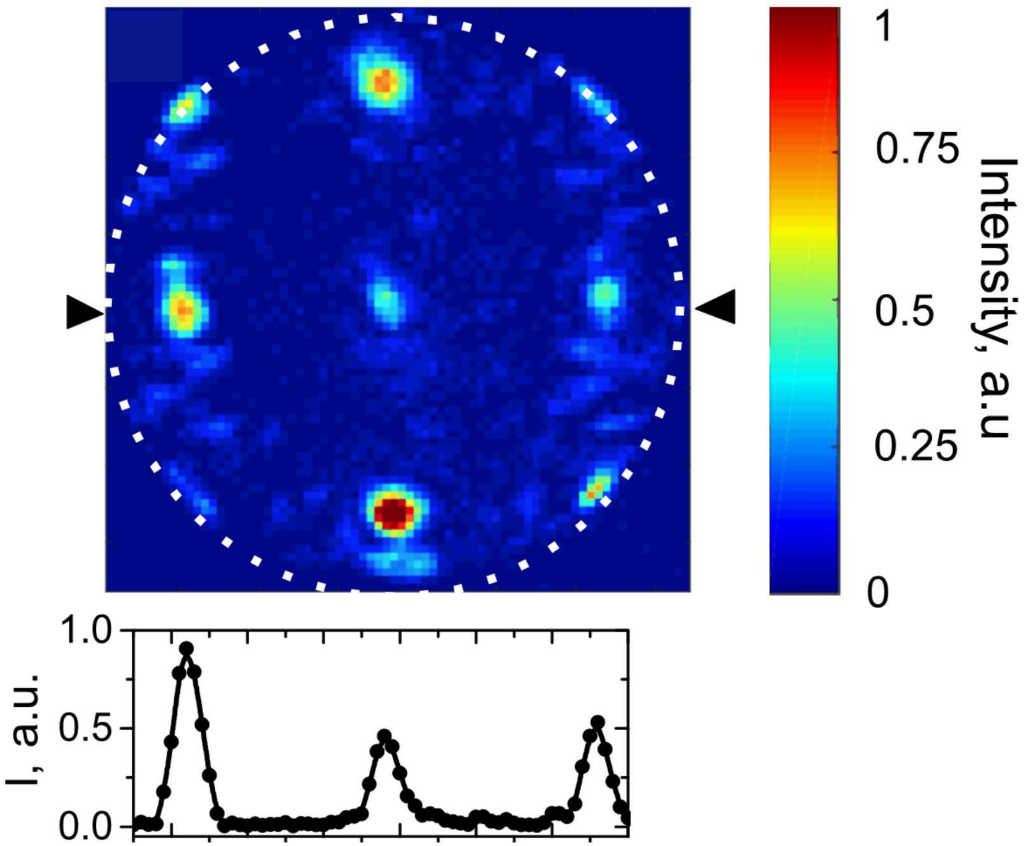


SHG enhancement at the wavelength of MD resonance

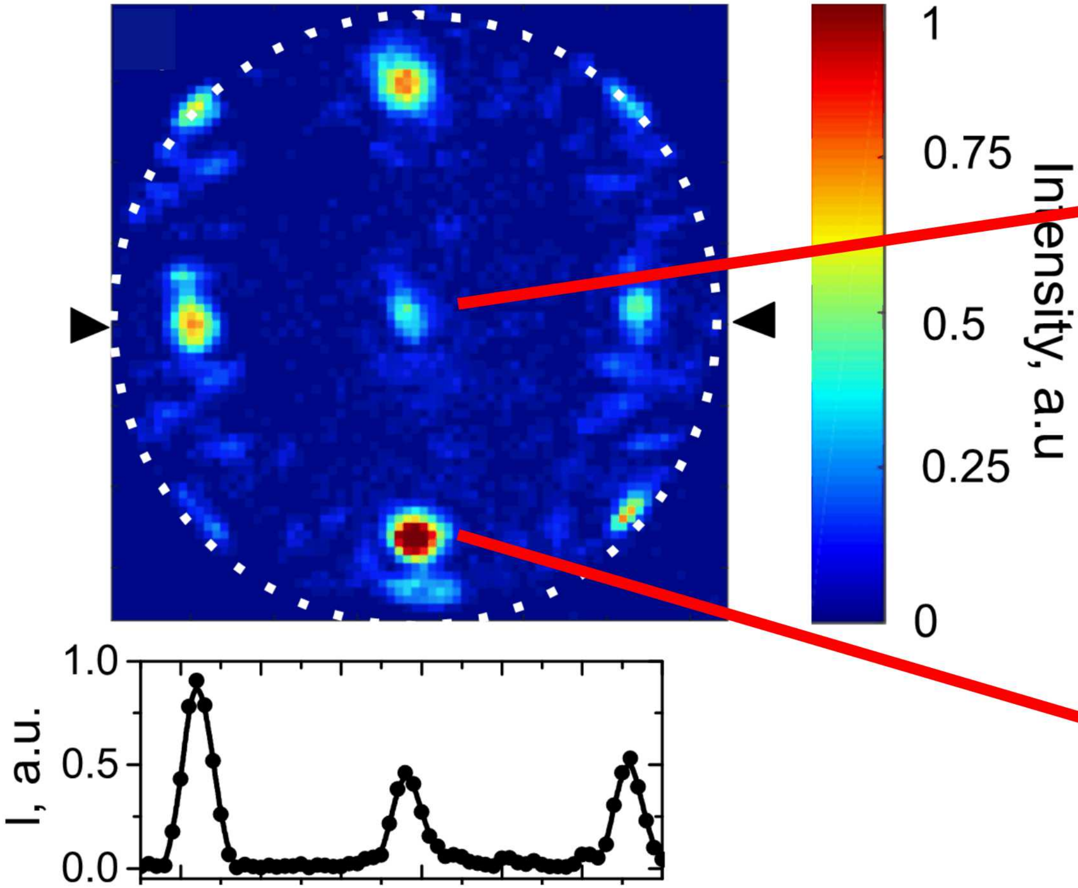
SHG in GaAs (111) metasurface: Fourier-space image



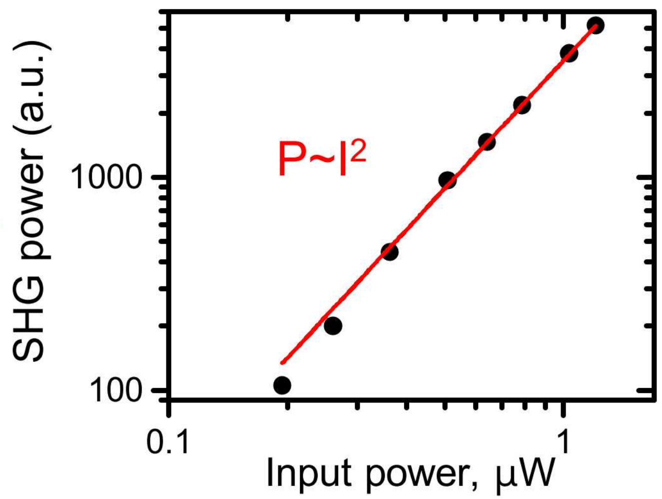
SHG enhancement at the wavelength of MD resonance



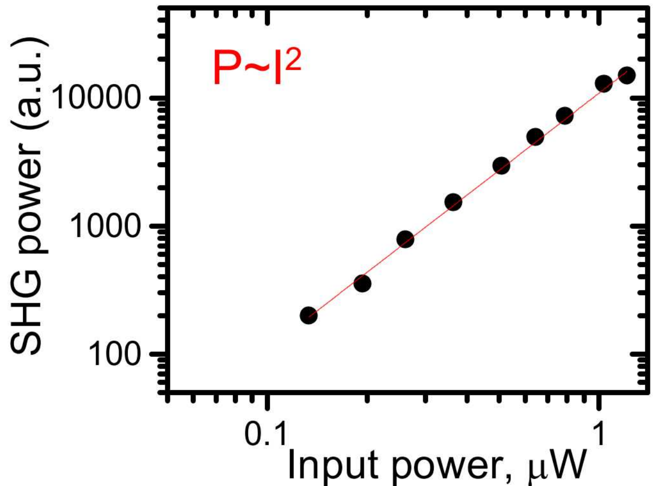
SHG in GaAs (111) metasurface: Fourier-space image



Power dependence for the zeroth-order diffraction

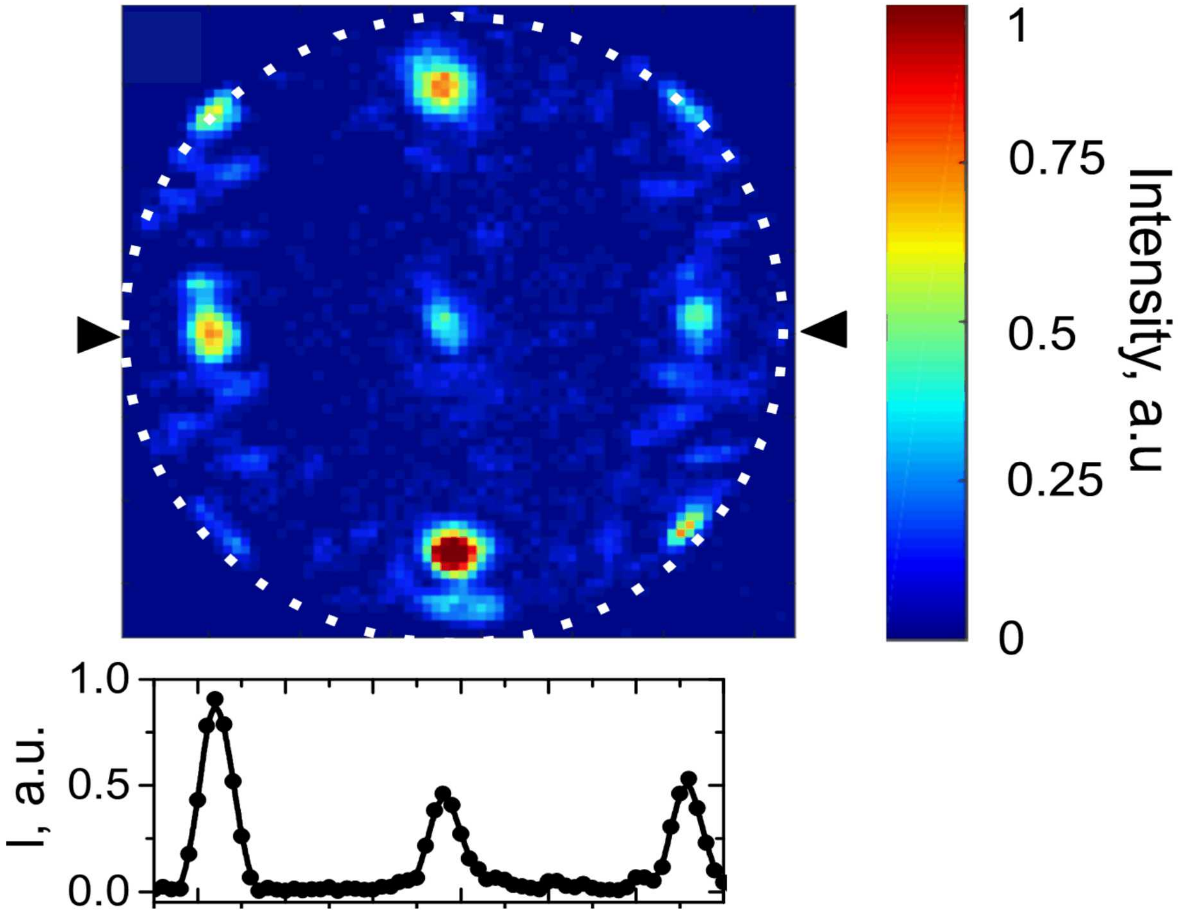


Power dependence for the bottom diffraction peak

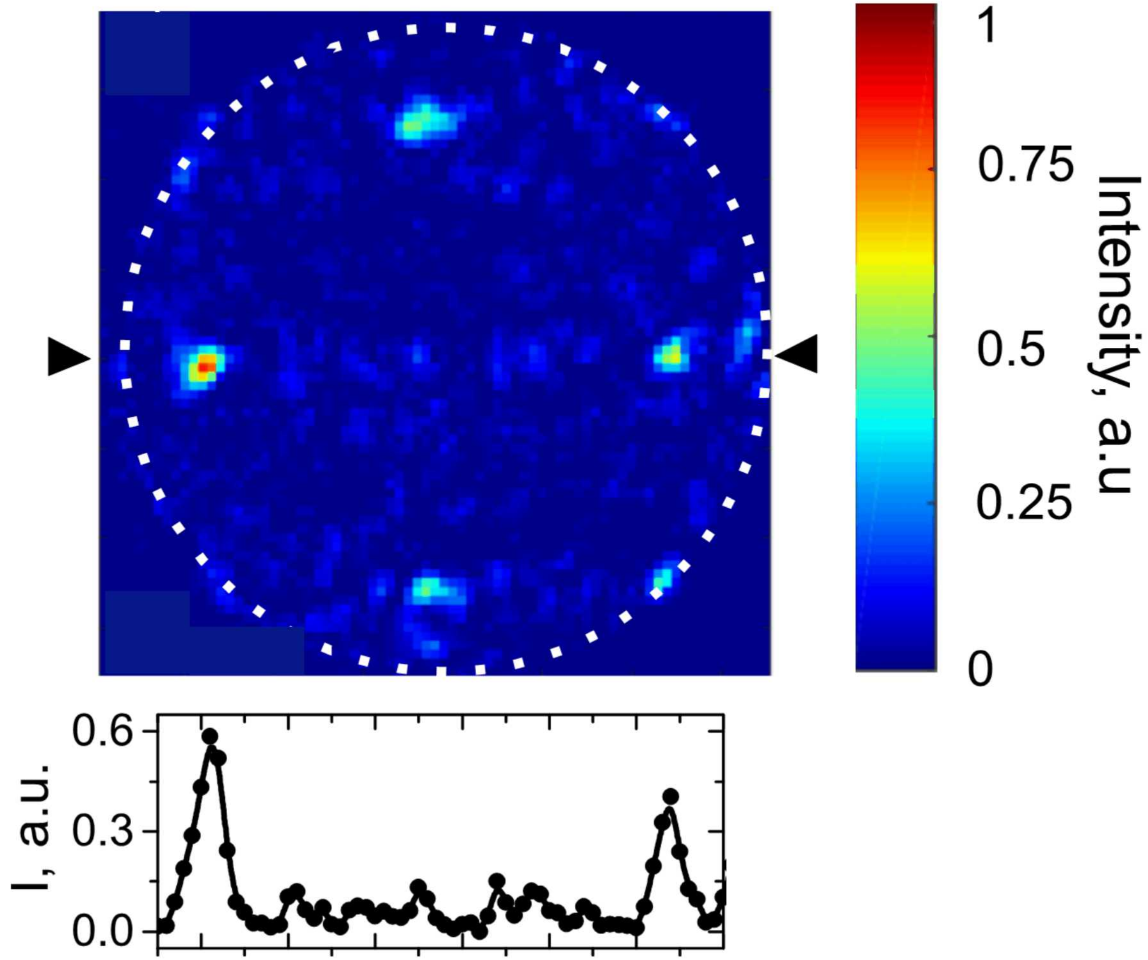


Comparison: Fourier-space images for metasurfaces with different crystallographic planes

(111)

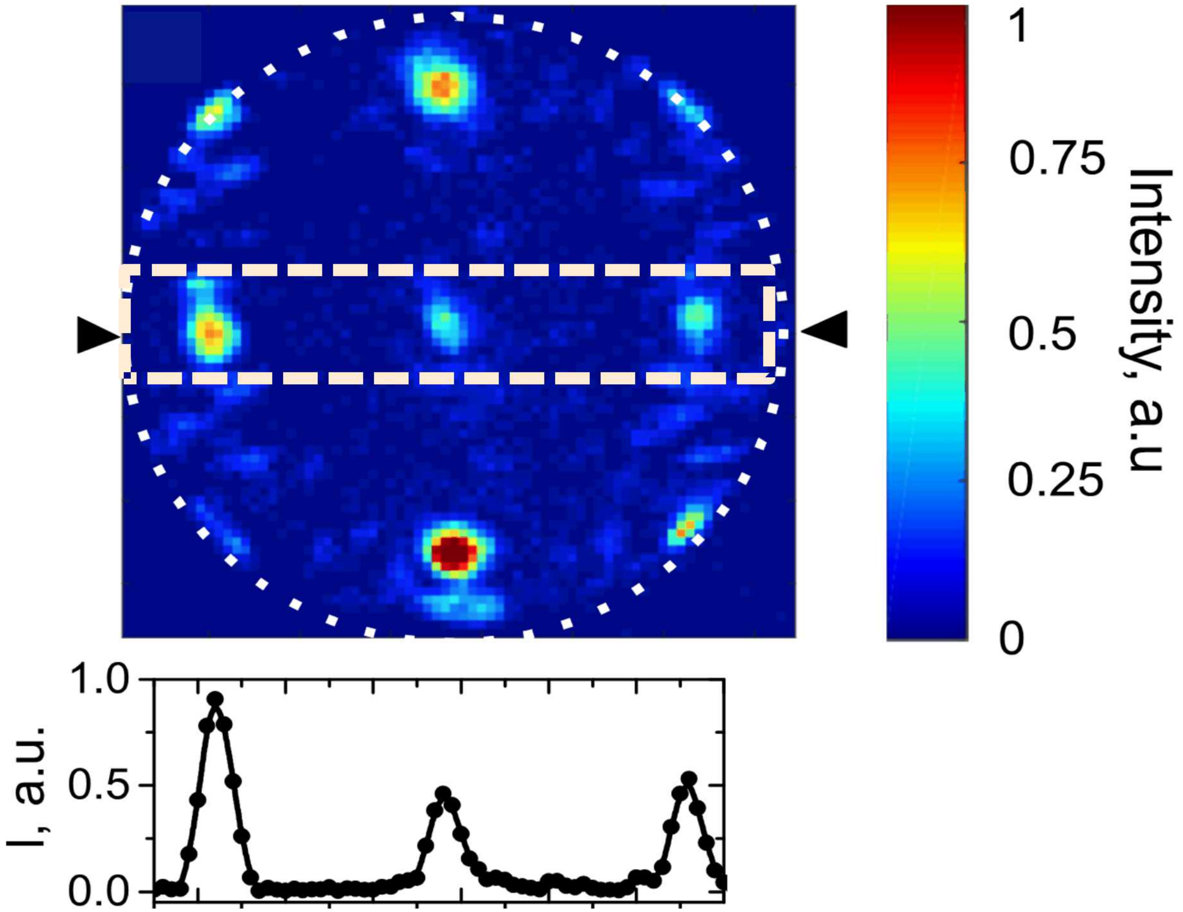


(100)

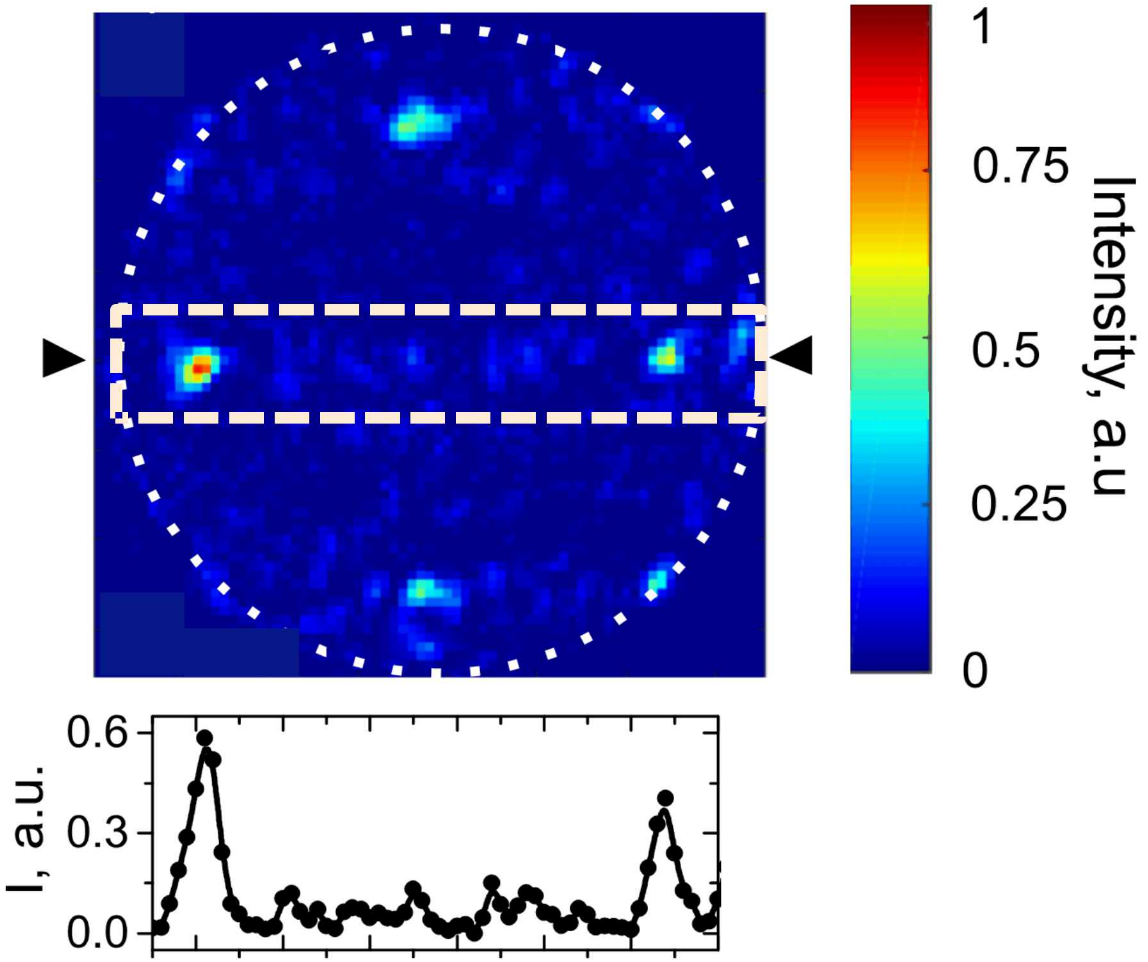


Comparison: Fourier-space images for metasurfaces with different crystallographic planes

(111)

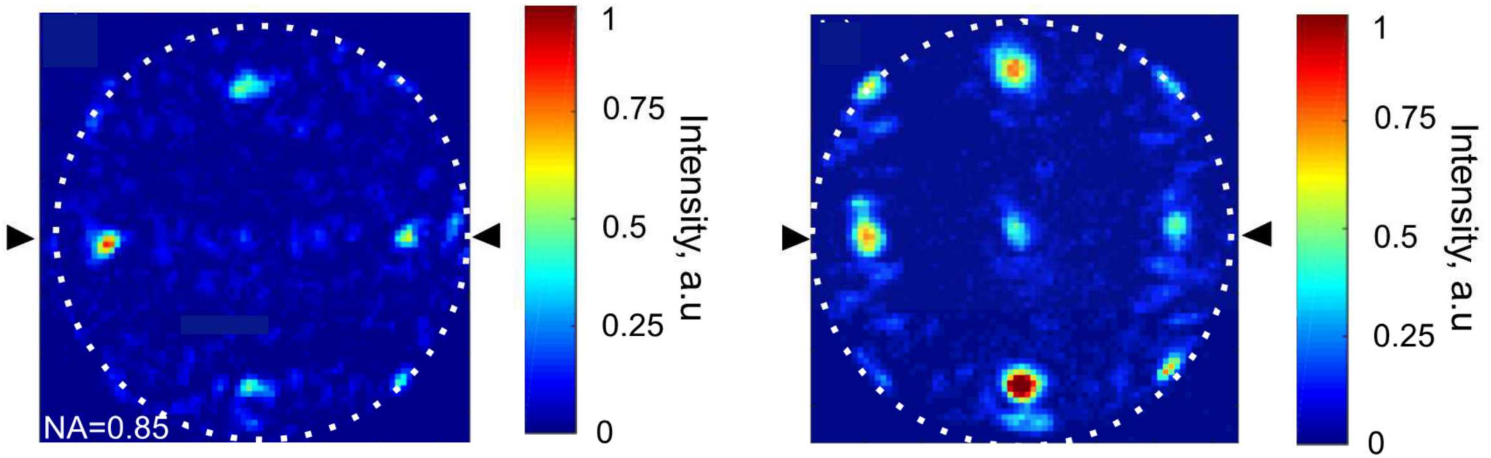


(100)

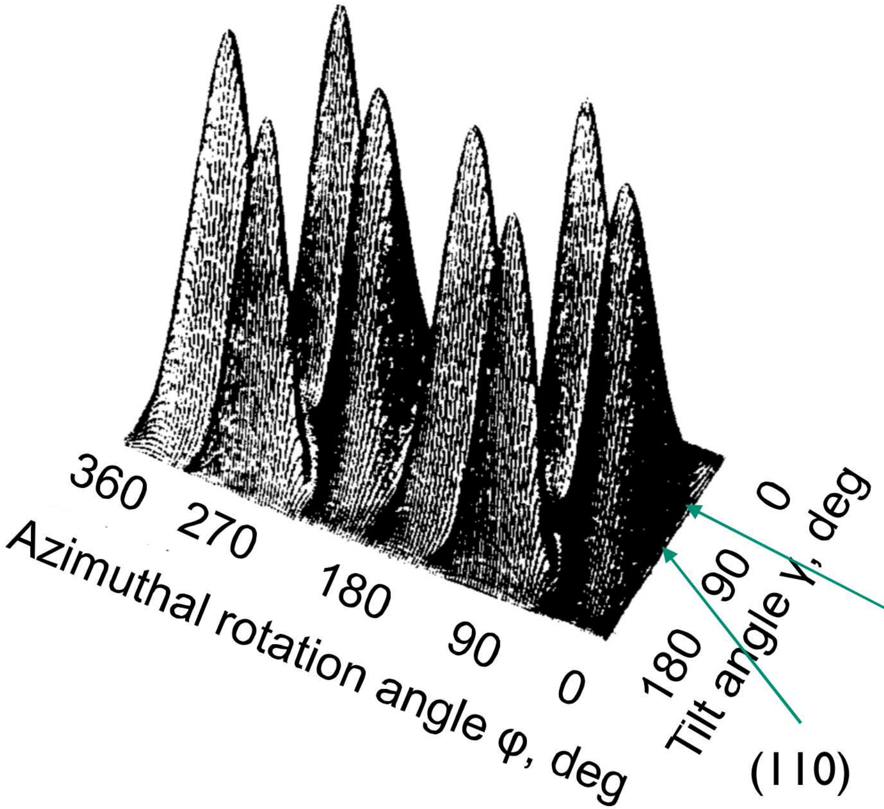


Conclusions

- We utilize III-V semiconductor metasurface fabricated from GaAs grown on (111) lattice plane to control the spatial distribution of the SHG intensity.
- By changing the orientation of the GaAs crystal from (100) to (111) plane we were able to redistribute the SHG generation to the zeroth diffraction order.

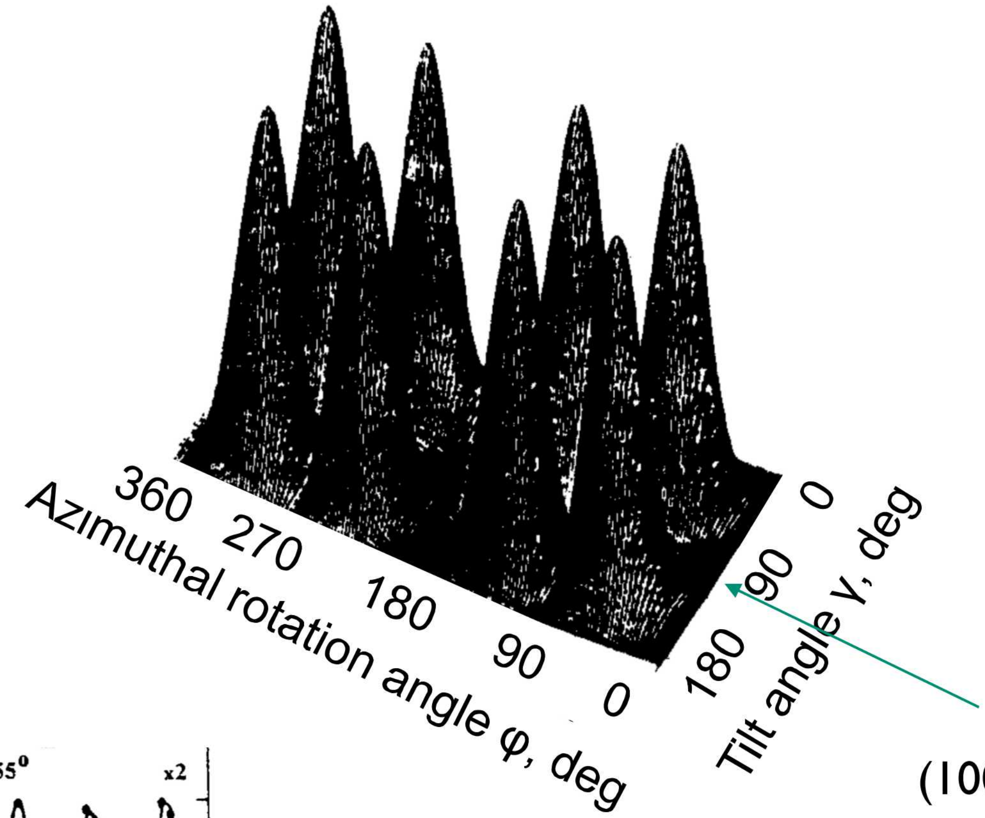


SHG for different orientations of the crystal, (111), (110), (100)

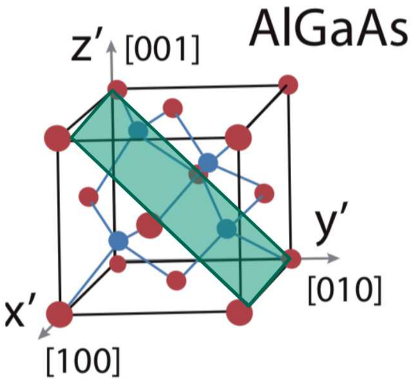


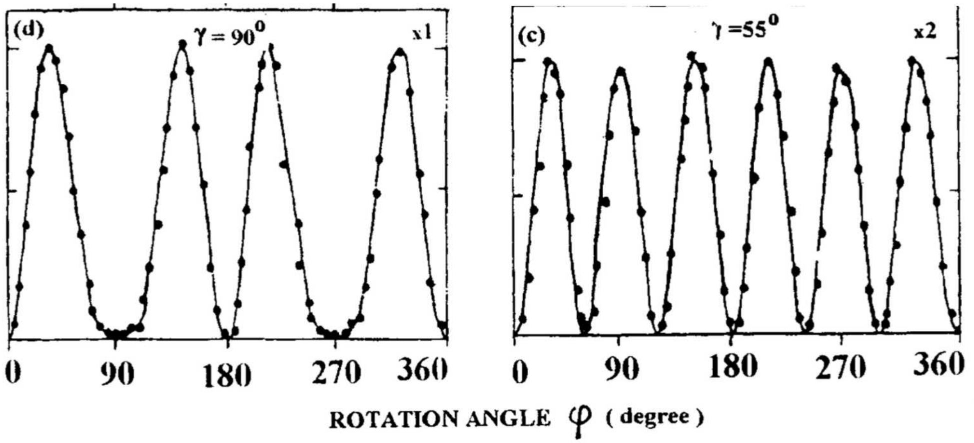
(110)

(111)



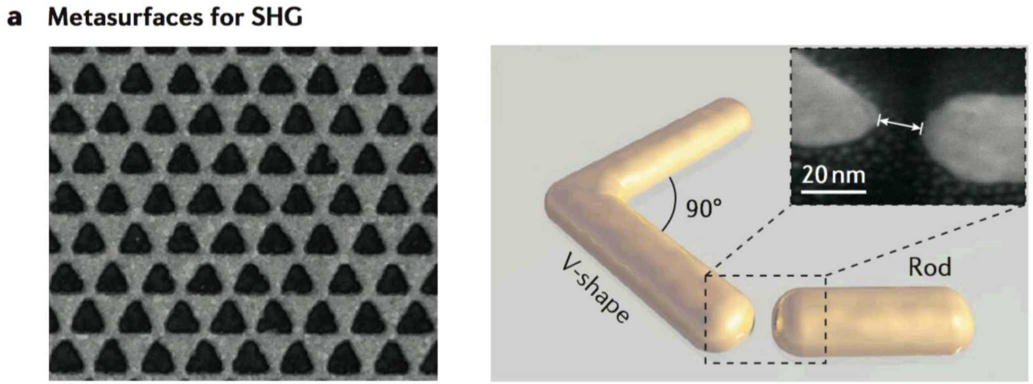
(100)



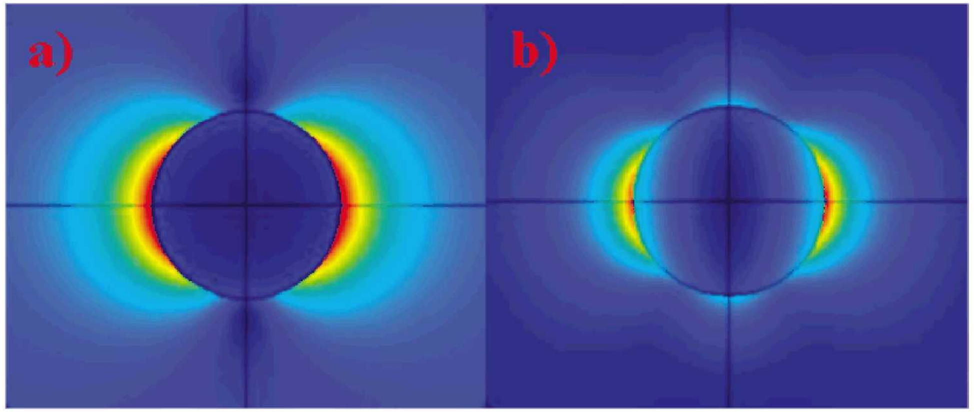


Kulyuk, Leonid L., et al. *Nonlinear Optics of Low-Dimensional Structures and New Materials*. Vol. 2801. International Society for Optics and Photonics, 1996.

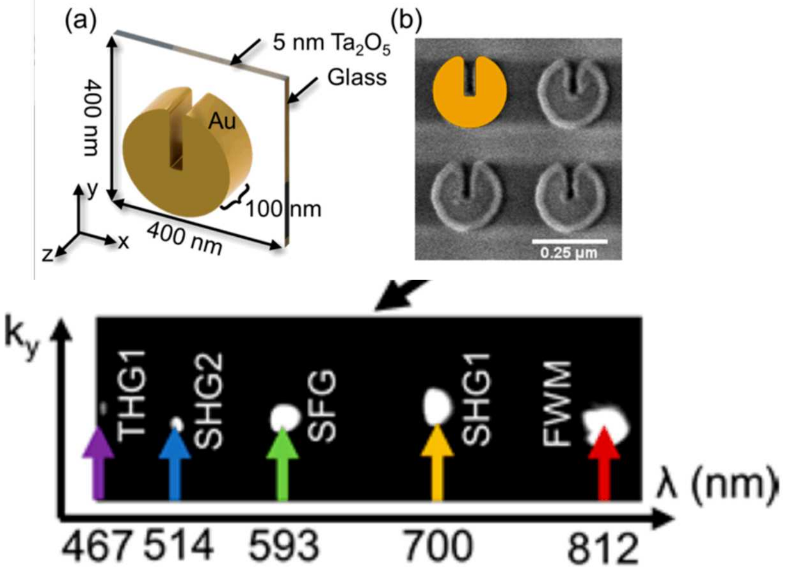
Nonlinear plasmonics



Li, G., Zhang, S. and Zentgraf, T., "Nonlinear photonic metasurfaces" *Nature Reviews Materials*, (2017), *2*(5), p.17010



Butet, Jérémy, et al. *Nano letters* 10.5 (2010): 1717-1721.



Sartorello, et al. *ACS Photonics* 3.8 (2016): 1517-1522.

Plasmonic metasurfaces:
- Ohmic losses
- Plasmonic structure: small modal volume (surface nonlinearities)

SHG efficiency ~ 5.1×10^{-10} W/W^2

Reflectance spectrum