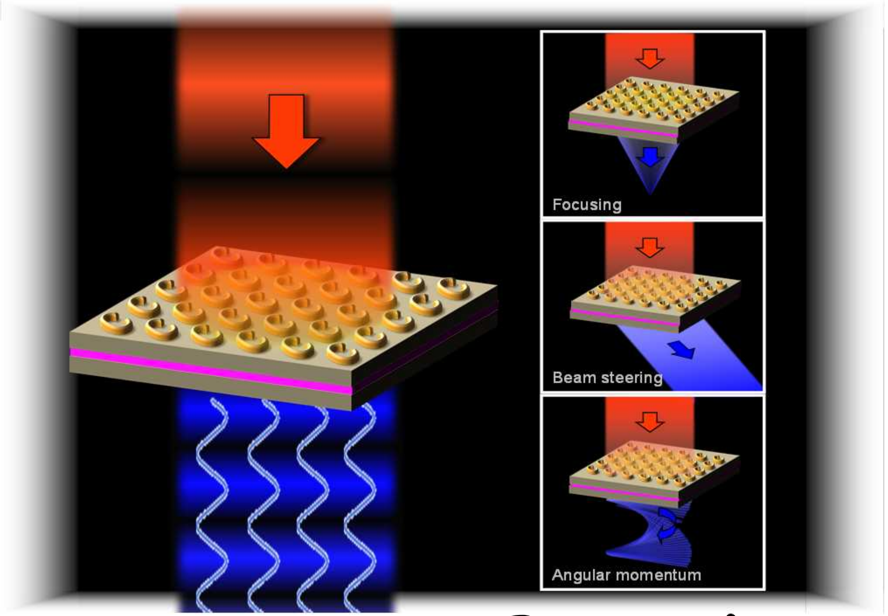

SAND2015-6532C

Phased-Array Sources Based on Nonlinear Metamaterial Nanocavities

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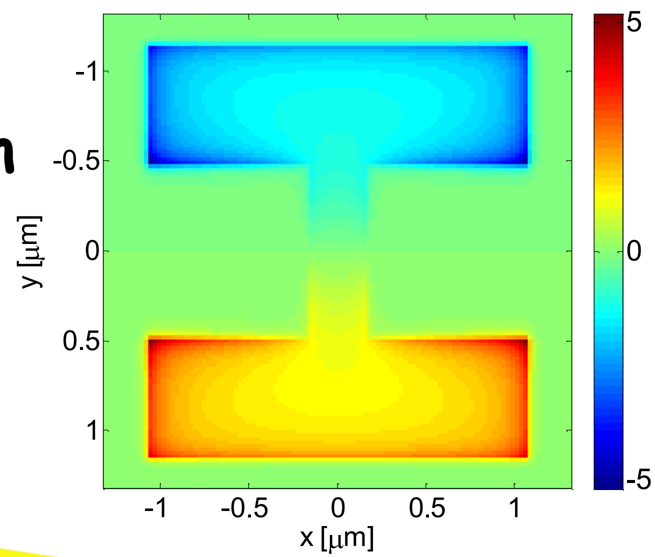
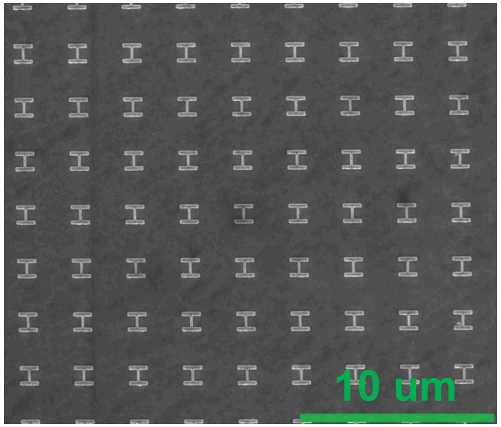
Outline

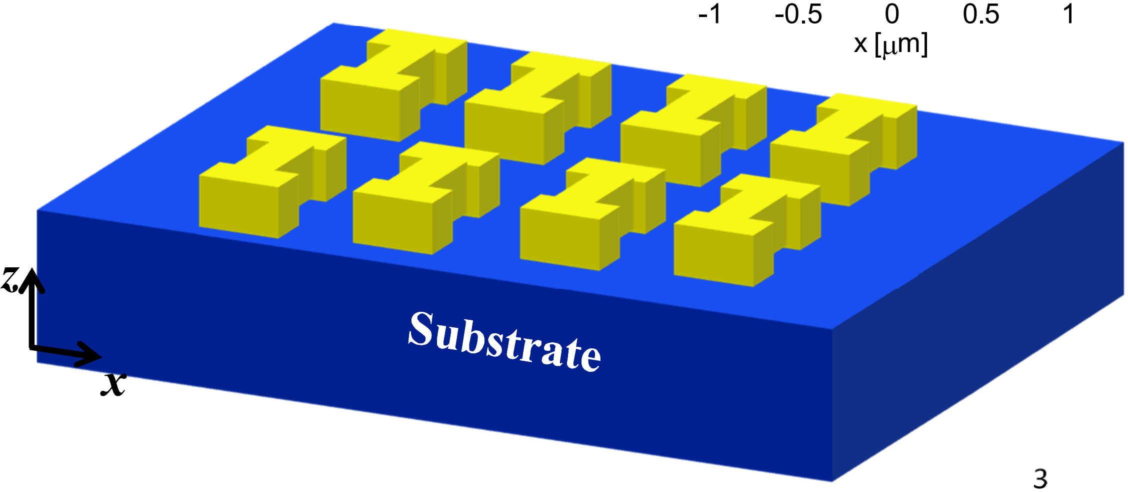
- **Intro to metasurfaces, intersubband transitions**
- **Strong light-matter interaction**
- **Nonlinearity in intersubband transitions of quantum-wells:**
    - giant $\chi^{(2)}$ but only in z direction
- **A doubly resonant nanocavity:**
    - Fully engineerable resonances
    - Field enhancement
    - Phase control
- **Putting it all together: an IR source with a engineerable beam shape**

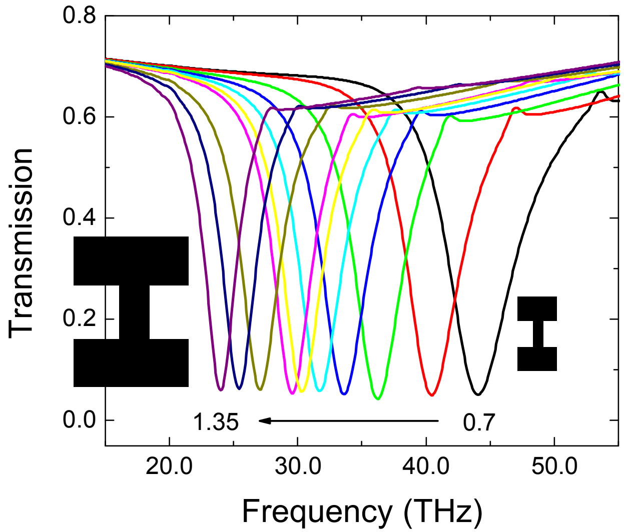
Metasurface - Array of optical cavities

- Resonance of single cavity induces effect on transmission of the array

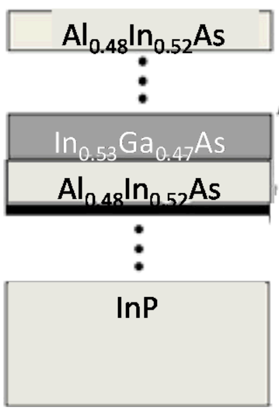


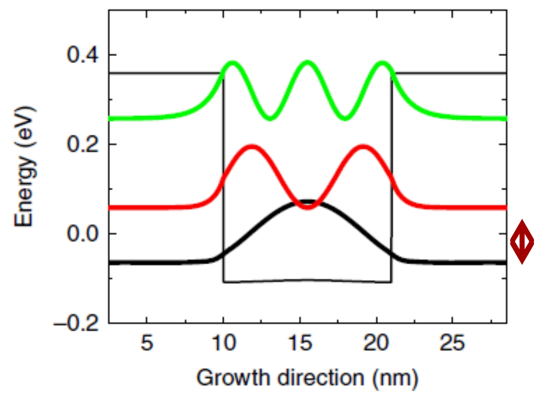






A matter of resonance: Intersubband transitions in quantum wells





- Conduction band is quantized in growth direction
- Transitions are optically active

L. C. West and S. J. Eglash, Appl. Phys. Lett., **46**, 1156-1157, (1985)

InGaAs homogeneously doped

E. Ro

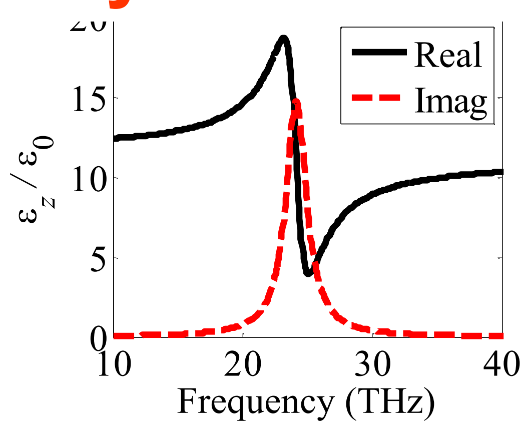
Only z polarized light can interact with the QWs and excite the optically active transition

Opt ... tor in z direction only

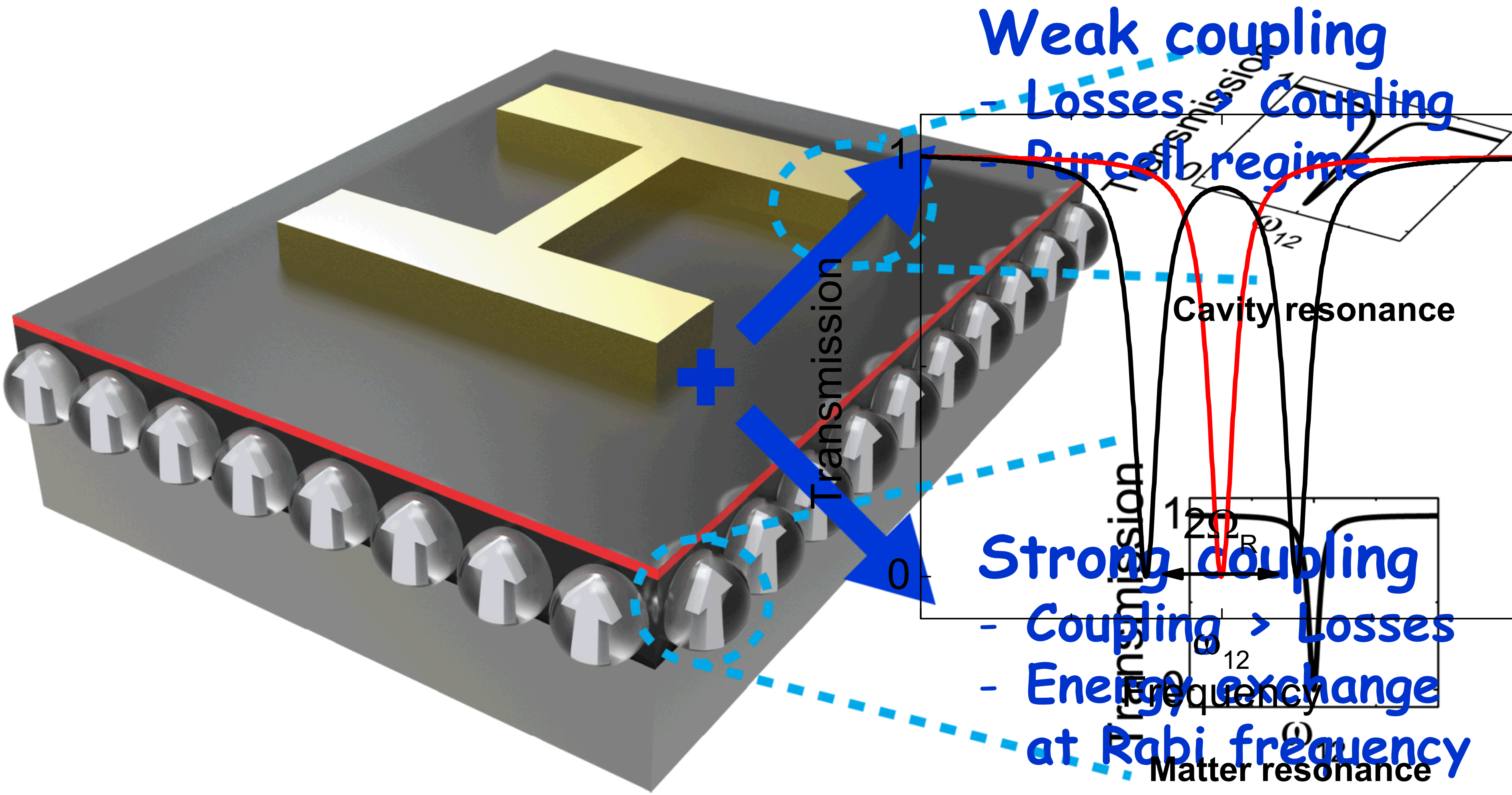
$$\underline{\boldsymbol{\varepsilon}}_{\mathrm{IST}} = \varepsilon_b\left(\hat{\mathbf{x}}\hat{\mathbf{x}} + \hat{\mathbf{y}}\hat{\mathbf{y}}\right) + \varepsilon_z \hat{\mathbf{z}}\hat{\mathbf{z}}$$

$$\varepsilon_z = \varepsilon_b + \chi \qquad \varepsilon_b = 11\varepsilon_0$$

$$\chi = \frac{Ne^2}{m^*} f \frac{1}{\omega_0^2 - \omega^2 - 2i\gamma\omega}$$

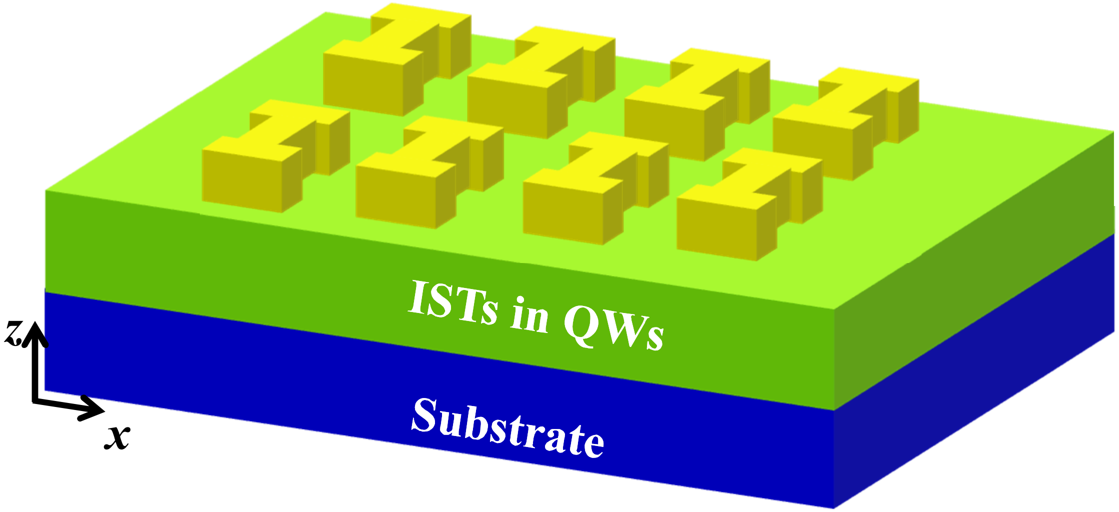


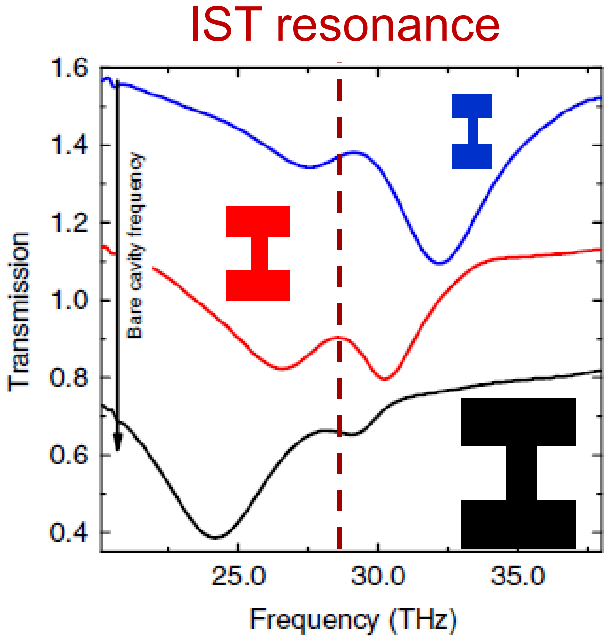
Light-matter coupling in metasurfaces



Benz et al., *Nature Commun.* 4, 2882 (2013)

Observing Strong coupling

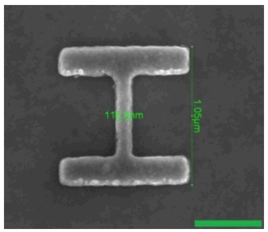


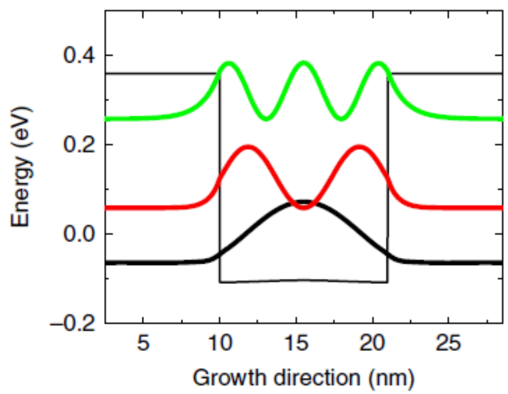


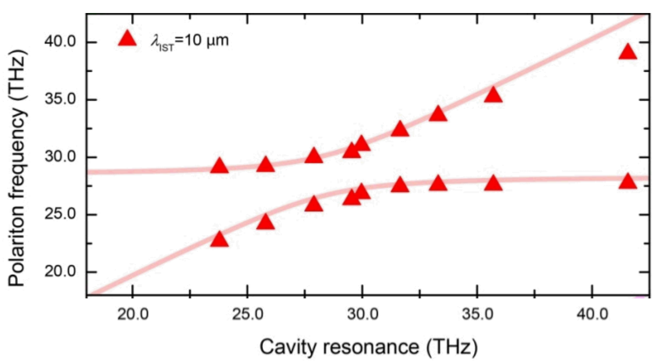
Strong coupling: from mid- to near-IR

InGaAs QWs **(mid IR)**

Benz et al., Nat. Commun. 4, 2882 (2013)



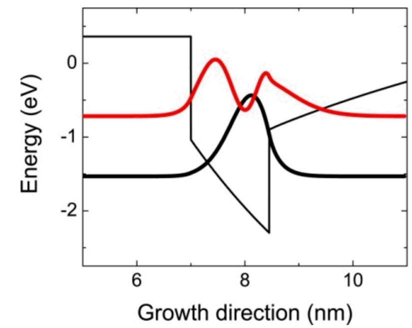


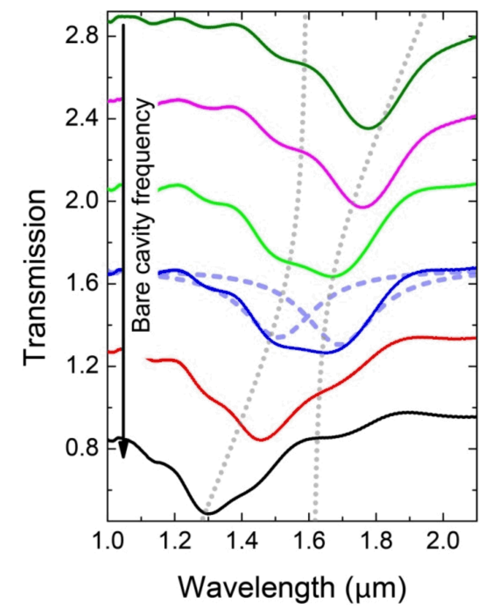


Alex Benz

GaN QWs **(near IR)**

Benz et al., ACS Photon. 1, 906 (2014)





Linear summary

- Metallic resonators have a fully tunable resonance

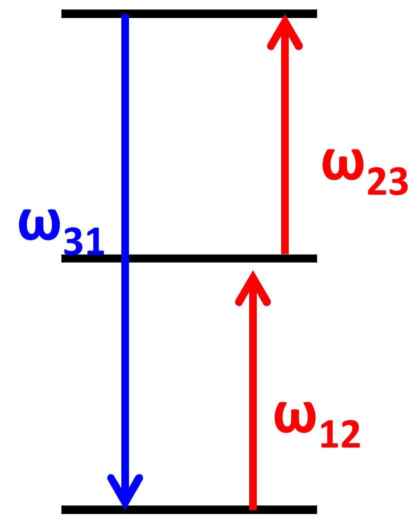
- Can be strongly coupled to matter resonances
  - energy is transferred back and forth: matter ←→ light

- Works througout most of IR

Resonant $\chi^{(2)}$ and Intersubband Transitions in Quantum-Wells

3-level systems exhibit resonant $\chi^{(2)}$.

Properly designed ISTs exhibit <u>very high</u> resonant $\chi^{(2)}$



$$\chi^{(2)}(\omega) \propto \frac{N \cdot z_{12} z_{23} z_{13}}{(\omega - \omega_{12} - i\Gamma_{12})(2\omega - \omega_{13} - i\Gamma_{13})}$$

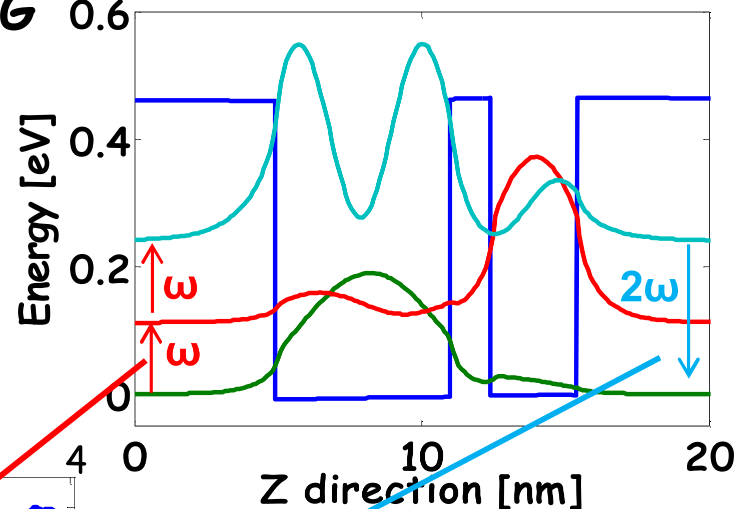
$$z_{ij} \propto \left\langle \Psi_i \middle| \vec{R} \middle| \Psi_j \right\rangle$$

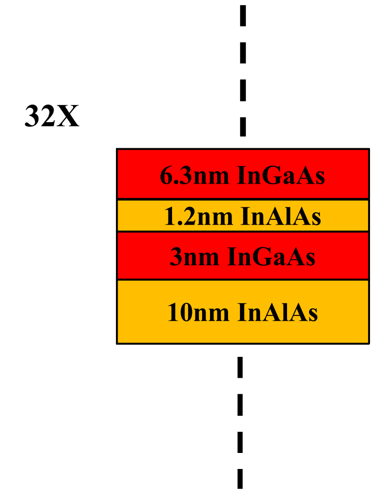
Design principles:

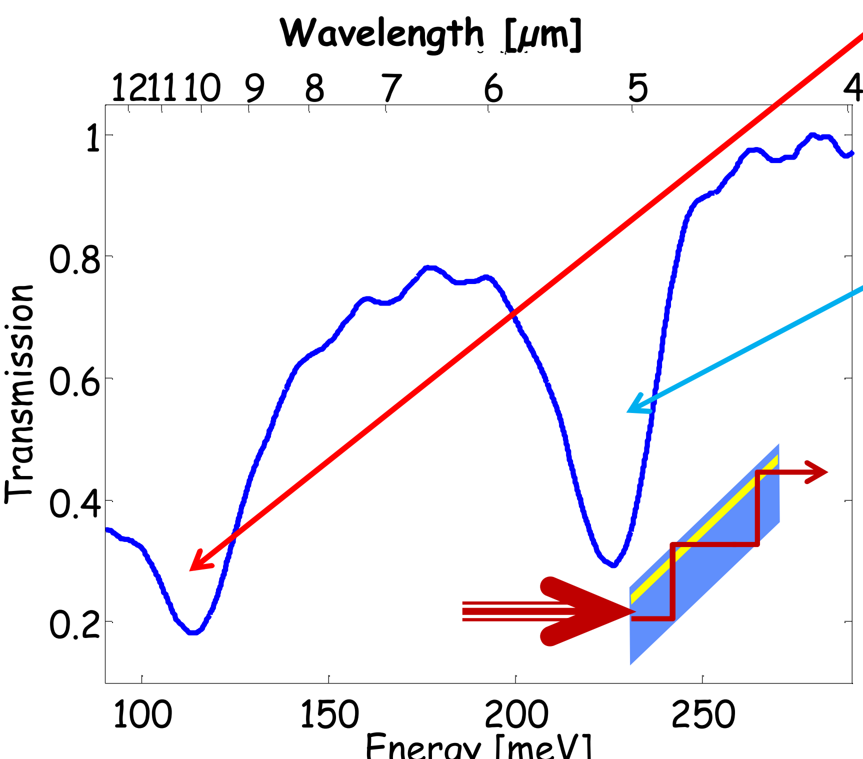
- Maximize carrier concentration in the wells.
- Maximize transition dipole moment.
- Levels equally spaced.
- Minimize losses

Our Nonlinear Medium

Design for 10μm → 5μm SHG
- -aysymetric double well
- -highly doped well







$\chi^{(2)}$ comparison

~250,000 pm/V - QWs

54.8 pm/V - $AgGaSe_2$

Caveat: $\chi^{(2)}_{zzz}$ only

F. Capasso, C. Sirtori, and A.Y. Cho, IEEE J. Quantum Electron. 30, 1313 (1994)
Rosencher et al. *Electron. Lett.* 25, 1063 (1989)
Khurgin *J. Opt. Soc. Am. B* 6, 1673 (1989)

resonant metamaterial for second harmonic generation

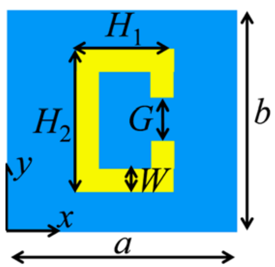
- Resonant metamaterials enhance second harmonic generation

Gorkunov et al. *Appl. Phys. Lett.* 88, 071912 (2006)
Klein et al. *Science* 313, 502 (2006)

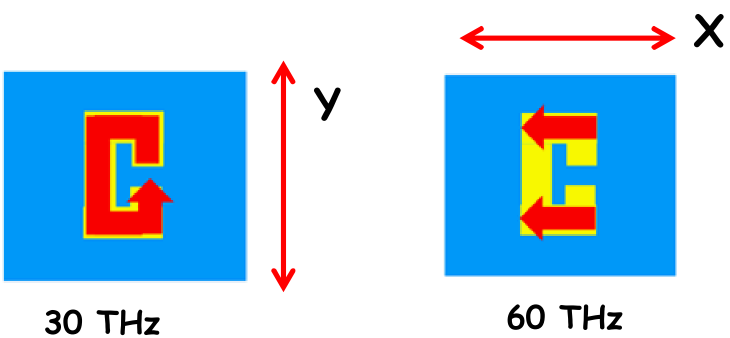
Kanazawa et al. *Appl. Phys. Lett.* 99, 024101 (2011)
Thyagarajan et al. *Opt. Express* 20, 12860 (2012)
Ginzburg et al. *ACS Photon.* 2, 8 (2014)

- We propose a split-ring resonator design supporting two resonances for orthogonal polarizations of the incoming wave

Proposed design

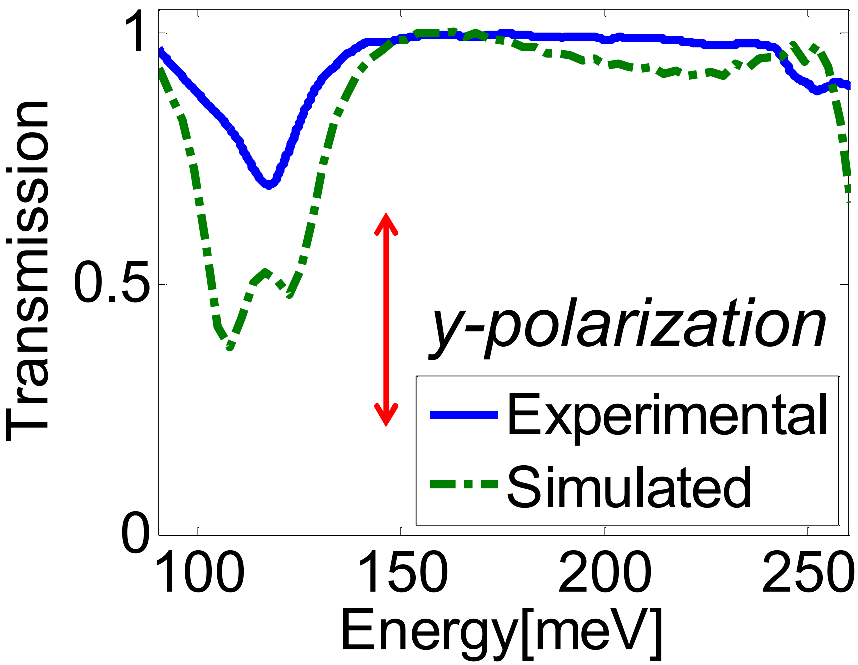


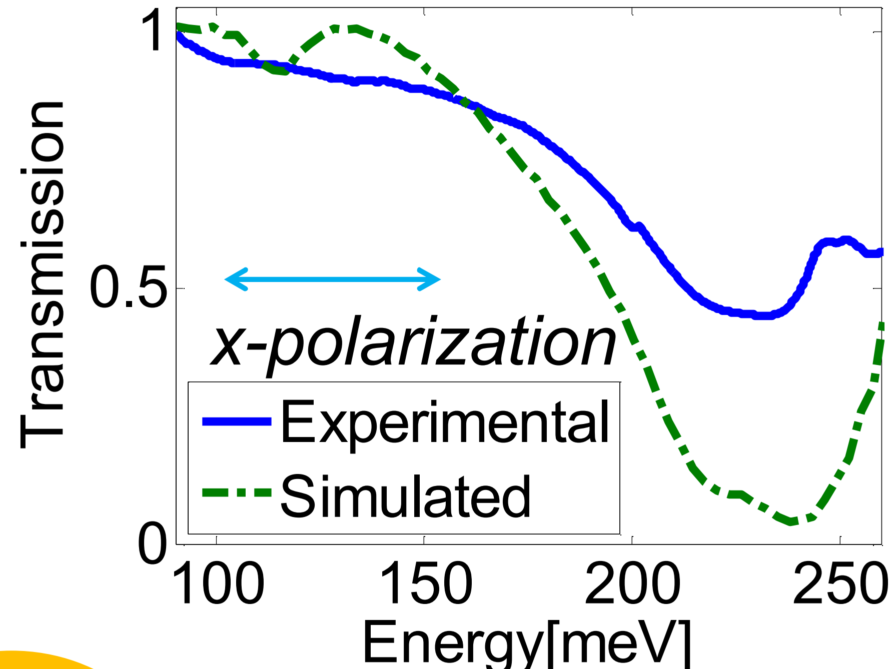
Supported resonances

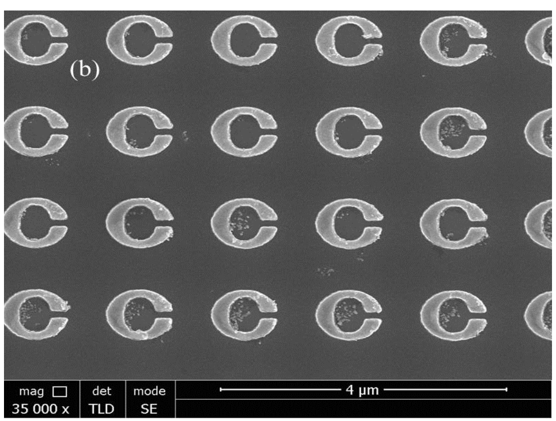


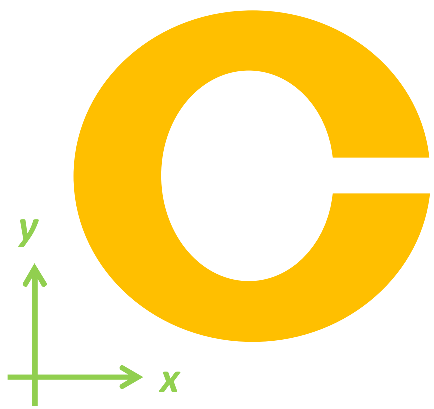
Campione et al. *Appl. Phys. Lett.* 104, 131104 (2014)

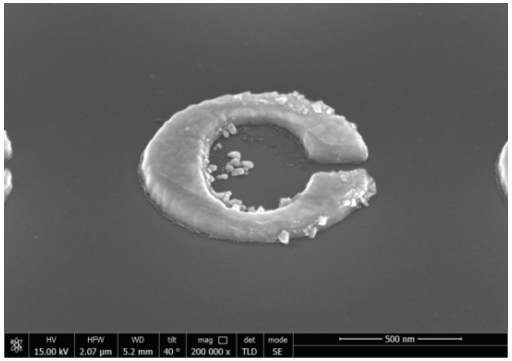
Nanocavity: doubly resonant design







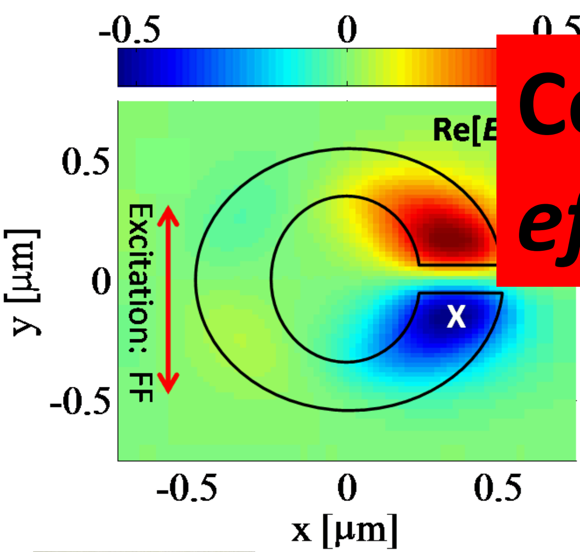




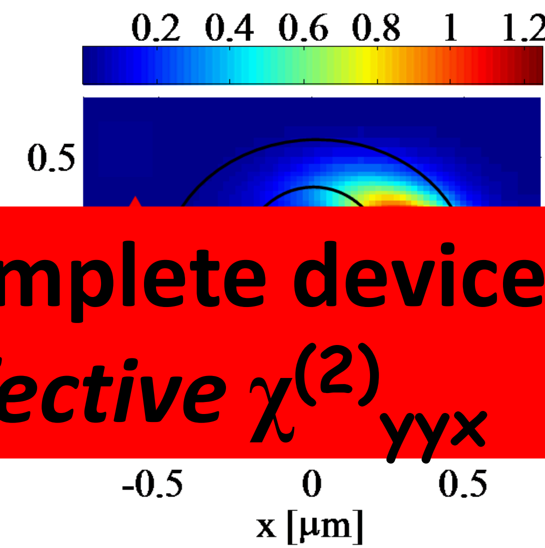
Nanocavity: Field Enhancement

Normal incidence 10μm plane wave excitation

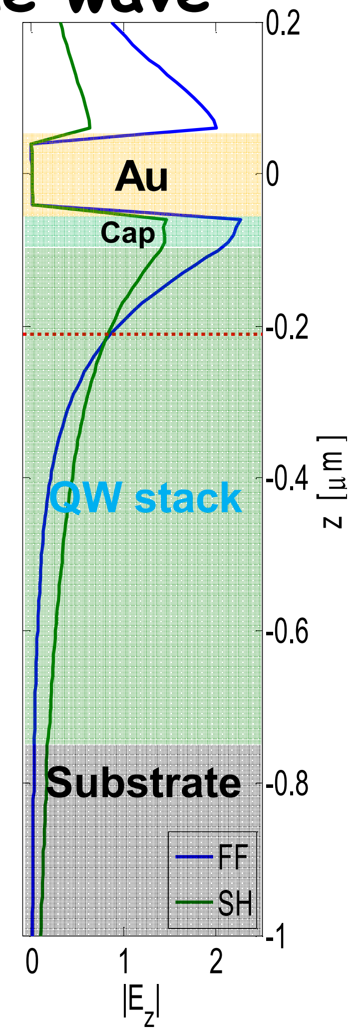
ω

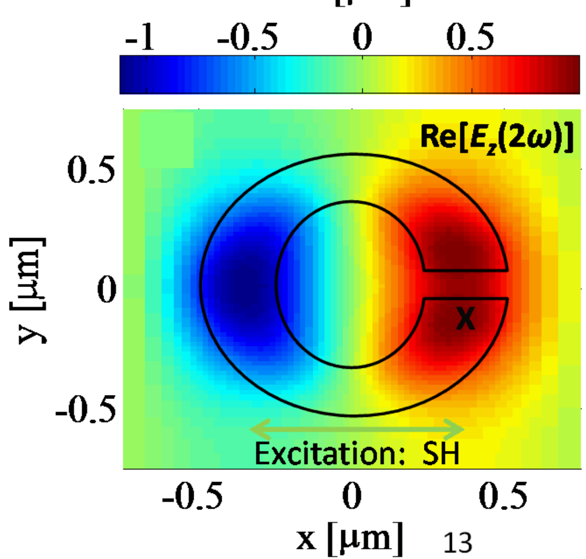


ω→2ω

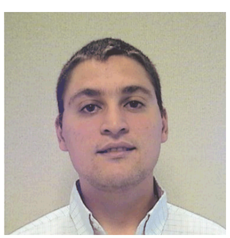


Complete device has *effective* $\chi^{(2)}_{yyx}$





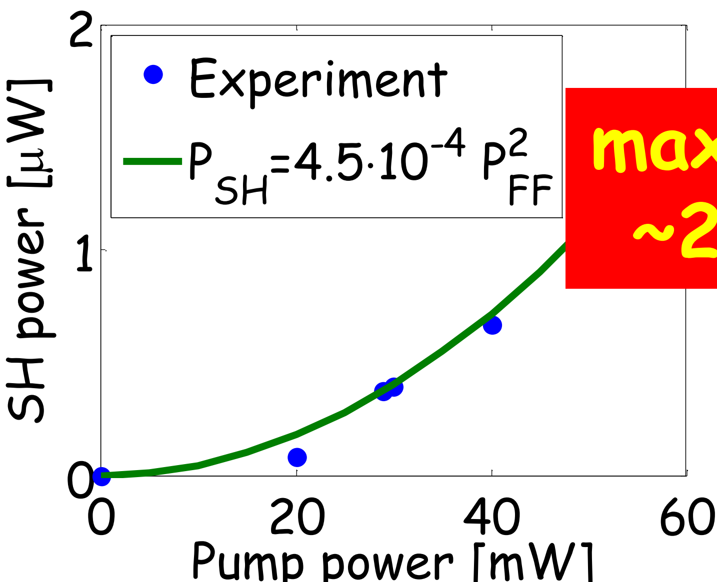
2ω



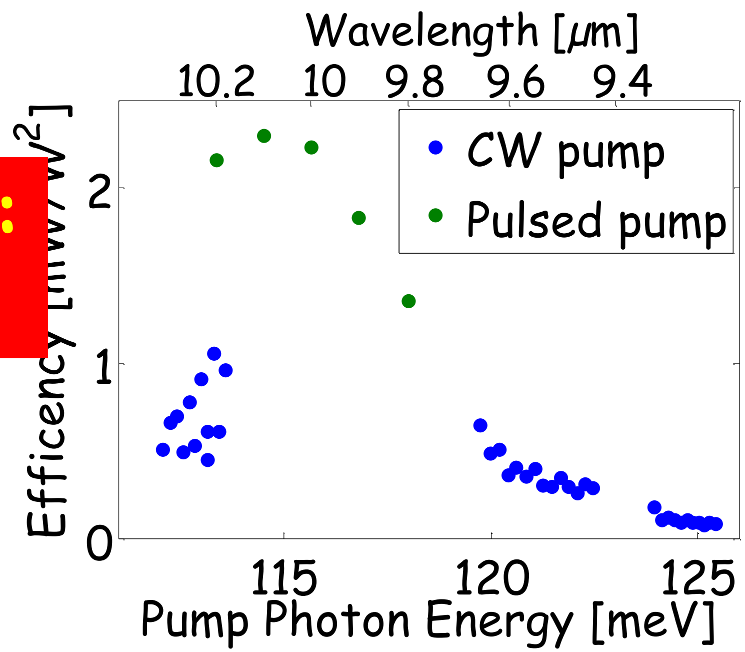
Dr. Salvatore Campione

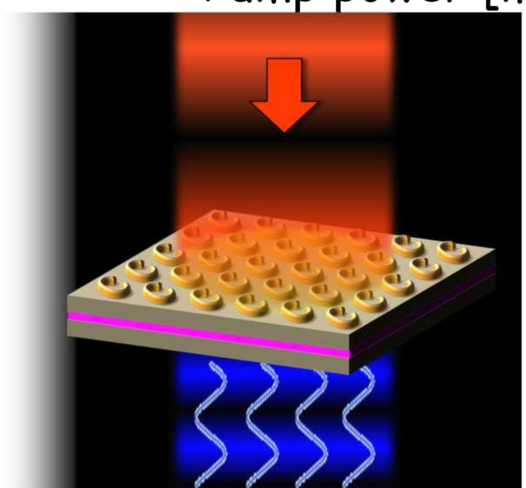
Power and Frequency Dependence

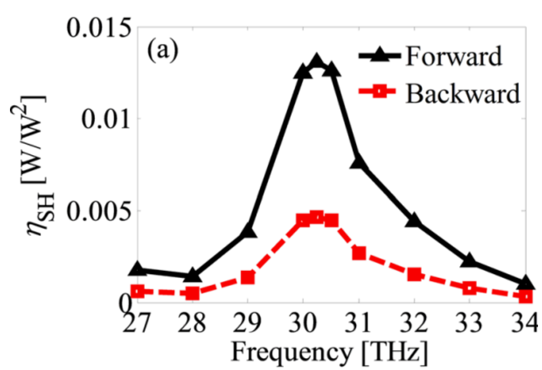
Pump is CW CO_2 laser



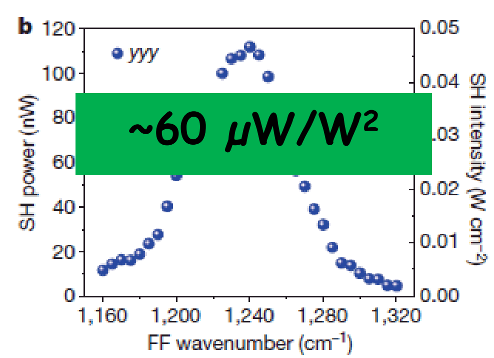
max efficiency: ~2.3 mW/W²







S. Campione et al. *Appl. Phys. Lett.* 104, 131104 (2014).



~60 μW/W²

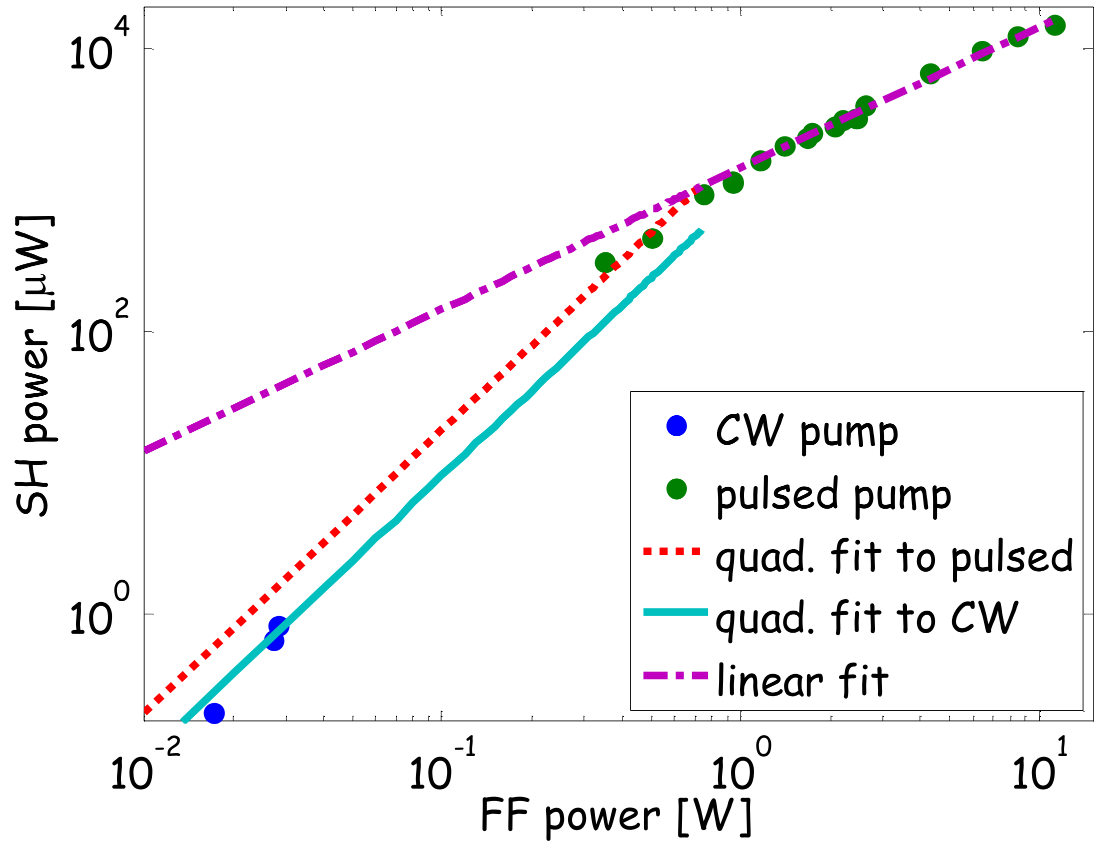
Lee et al. *Nature* 511, 65-69 (2014).

Saturation

- High pump intensity using pulsed OPA
- CW data shown at different frequency

max conversion: ~0.36%

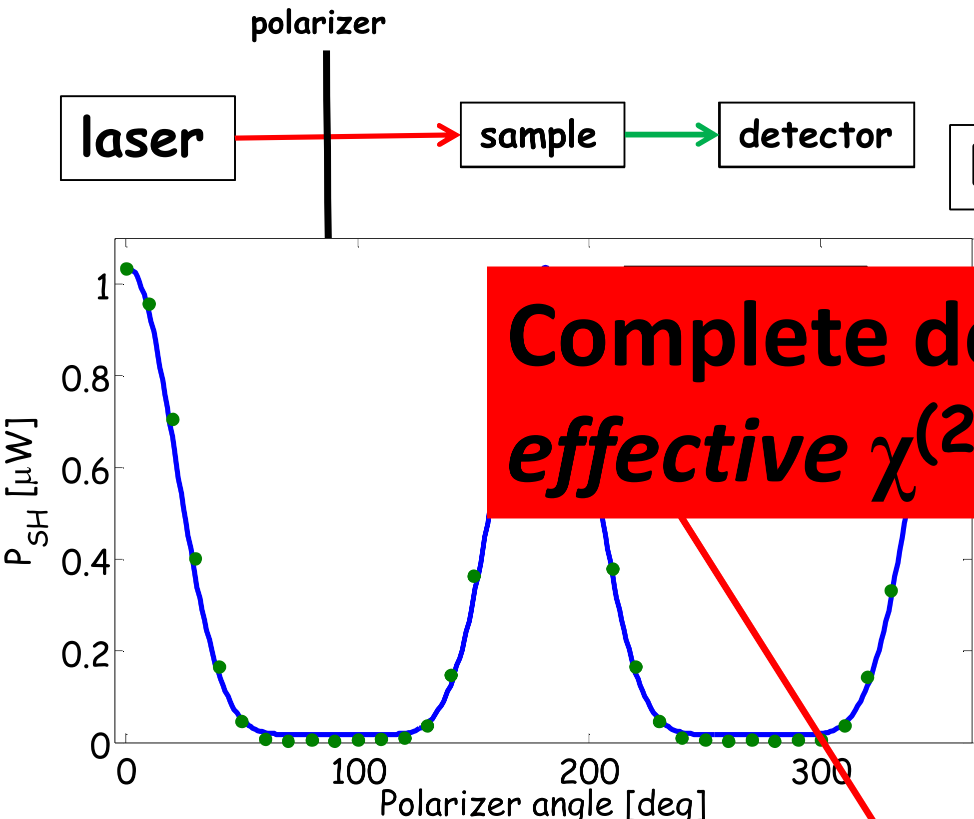
in ~700nm path length

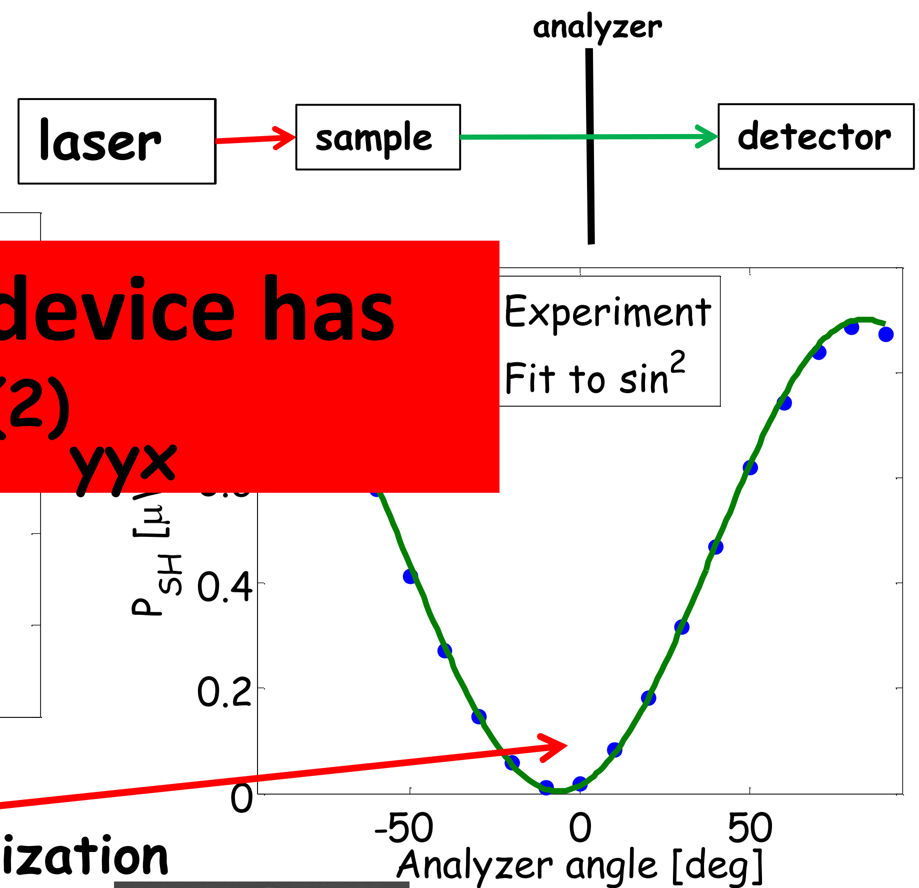


Pump: ~6kW/cm²

For bare QWs: MW/cm²

Polarization properties

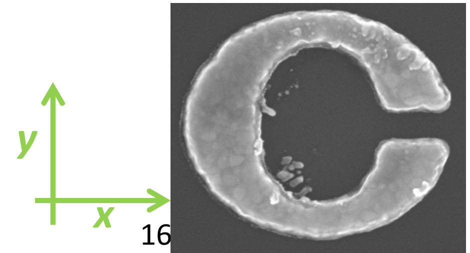




Complete device has *effective* $\chi^{(2)}_{yyx}$

laser polarization

out \ in	x	y
x	--	--
y	☺	--



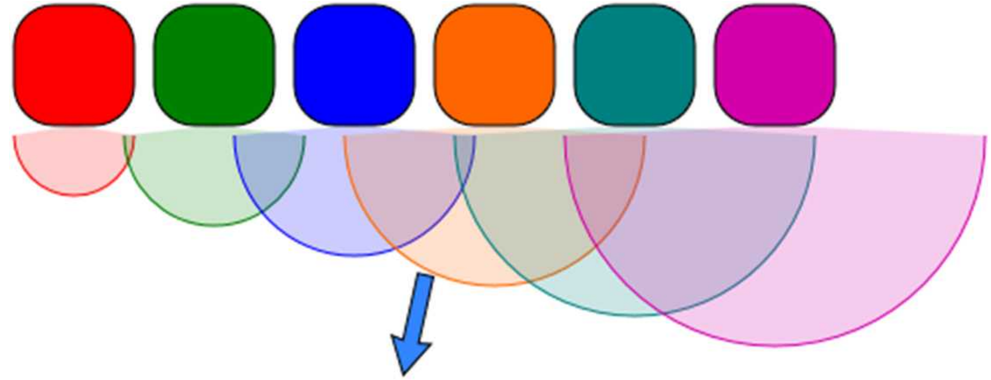
Second harmonic generation based source

- Subwavelength source based on second harmonic generation

- High efficiency considering an ultra-thin device

- Full polarization control at the source level

Phased Arrays



Identical point sources

+

Radiating with controllable phase difference

==

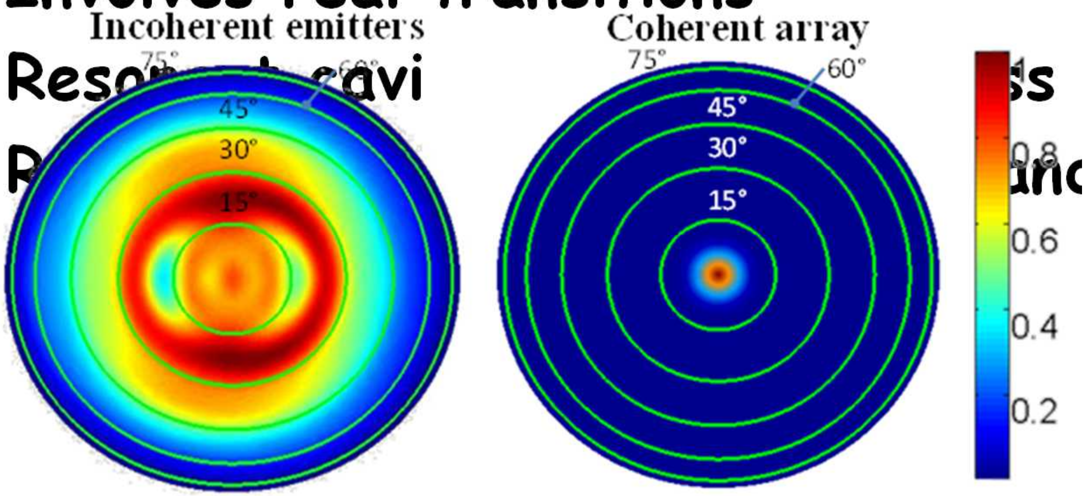
Full control over beam direction and shape

Image from Wikipedia

Coherence Demonstration

- Resonant p…cess → $\chi^{(2)}$ has phase
- Involves re… transitions
- Reso… cavi… …s
- R… …nc
-

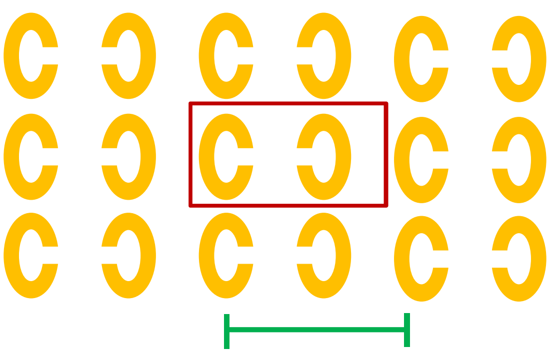
Simulation



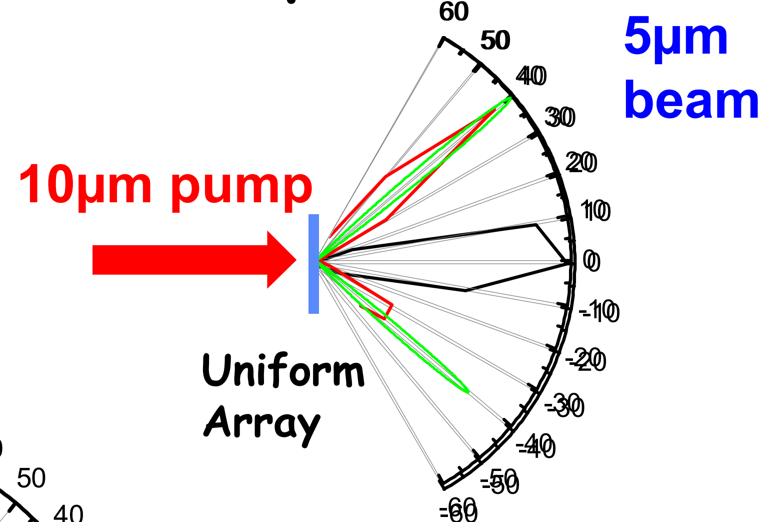
Beam Manipulation I

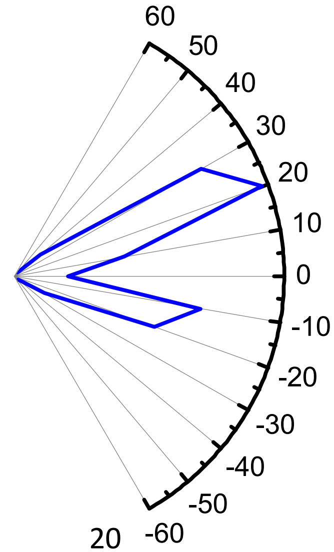
"edge-fed dipole"

flipping induces π phase shift



Period determines angular separation



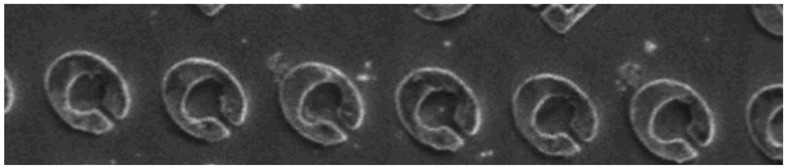


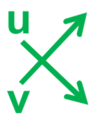
2-in-1:

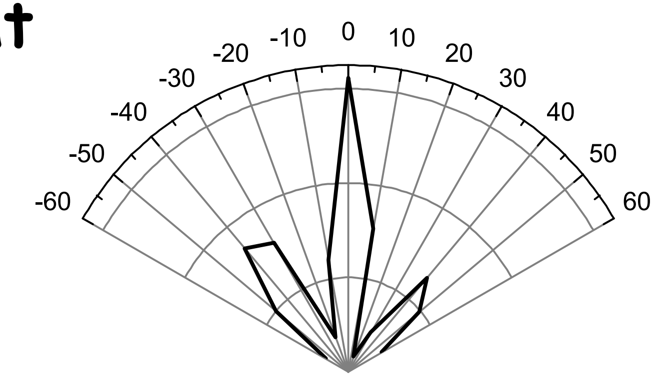
Source +beam splitter

Beam Manipulation II

- Cavities radiate polarized light

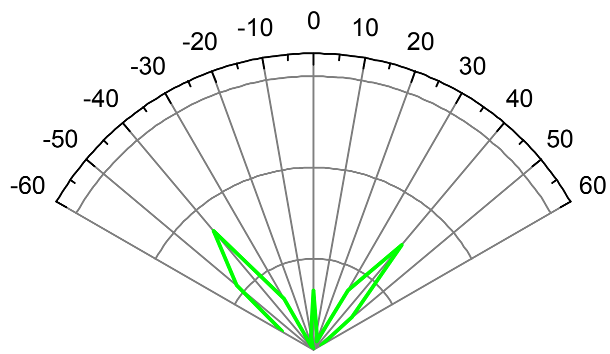




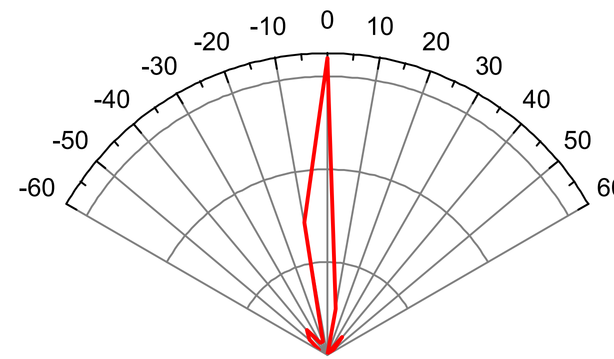


unpolarized

Pump polarization



v polarized



u polarized

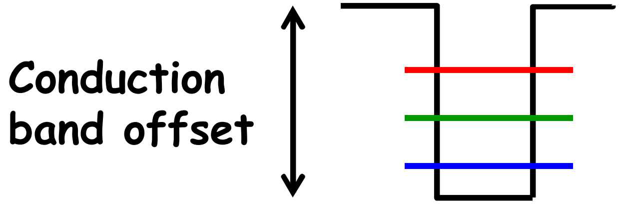
3-in-1:

Source +

Polarizer +

Beam Splitter

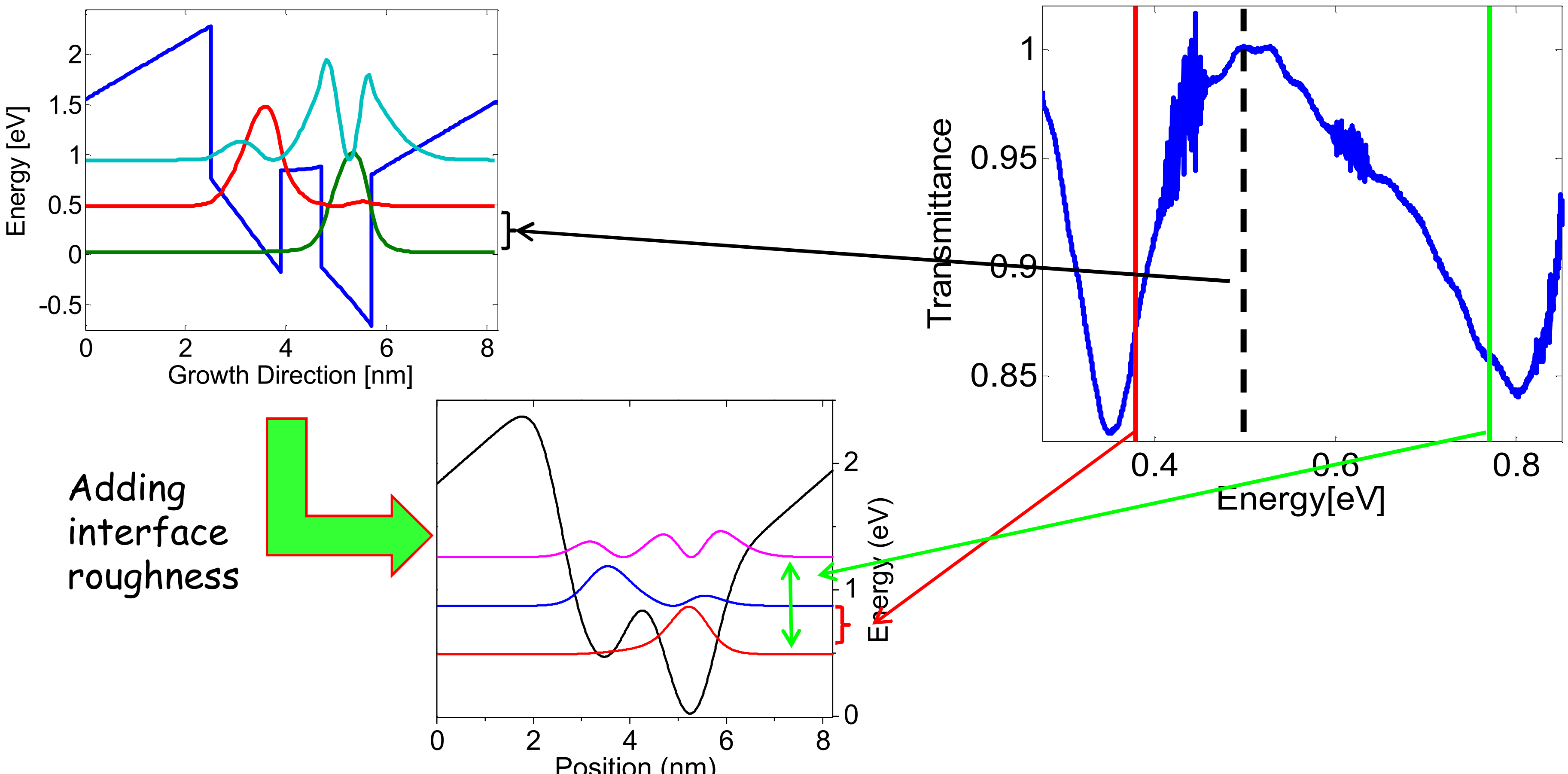
Moving to shorter wavelengths



- Challenges:
  - Very large CB offset required → III-Nitrides are hard to control
  - Resonators dimensions shrink → fabrication approaches the limit of conventional EBL
  - Metal losses increase → will strong coupling prevail??

SHG in III-N

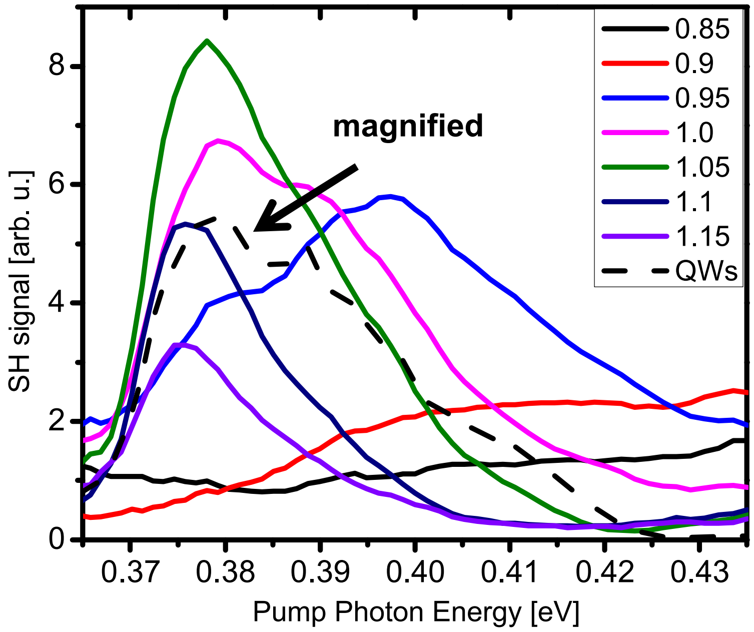
- Design: SHG 3 μm → 1.5 μm (0.4 eV → 0.8 eV)
- Traditional band structure calculation <u>not enough</u>
  - Over estimation of IST



O. Wolf et al. Under review

SHG in III-N

- Actual working wavelength 3.2 μm → 1.6 μm



- 2+ order of magnitude improvement

Summary

- SHG in **ULTRATHIN** device based on quantum-wells strongly coupled to metallic nanoresonators.
- **High Efficiency** operation in transmission.
  - SH is **cross polarized** from fundamental
  - Saturation observed
- **Coherent** SH radiation confirmed.
- Spatial and polarization **Beam Manipulation** demonstrated.
- Transition to **shorter wavelengths** via **III-N** demonstrated.

O. Wolf et al. *Nature Commun*. 6, 7667 (2015)
S. Campione et al. *Appl. Phys. Lett.* 104, 131104 (2014).

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