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Engineerable Phased-Array Sources Based on Nonlinear Metamaterial Nanocavities

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Recipient of the 2015 IEEE Albuquerque Section Outstanding Young Engineer Award

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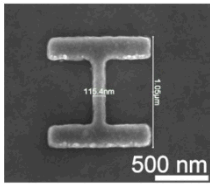
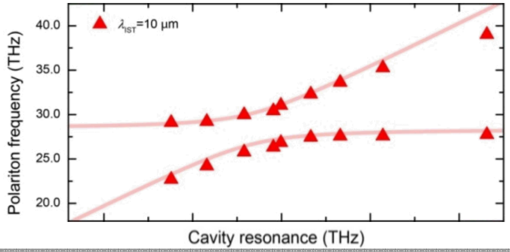
Outline of the Talk
Strong Light-Matter Interaction

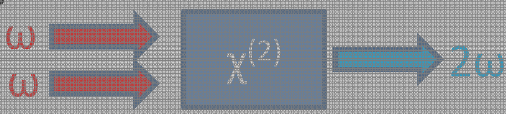
- Show how to use metamaterial nanoresonators to



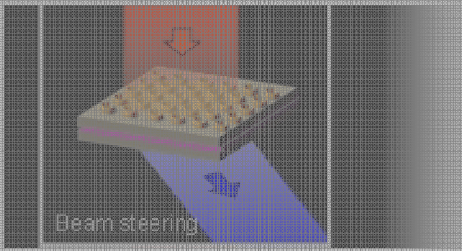
- Achieve strong coupling with intersubband transitions (ISTs) in quantum wells (QWs)



- Achieve efficient second harmonic (SH) generation in ISTs



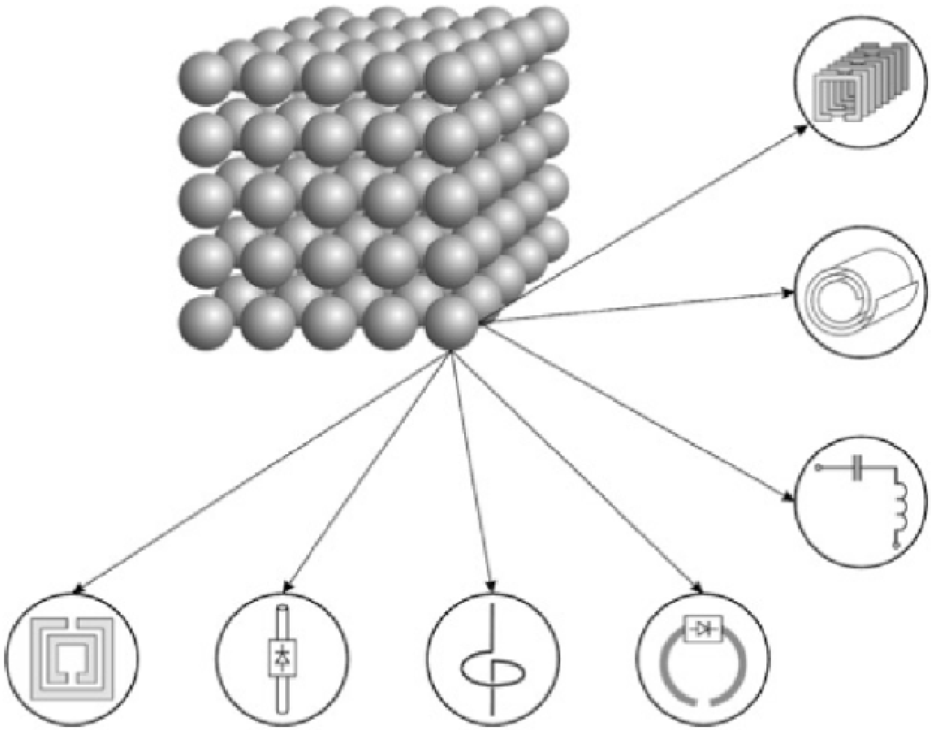
- Form a metasurface for beam manipulation of the SH signal



What are Metamaterials?

• Metamaterials are artificial materials whose interaction with light results in interesting phenomena otherwise unattainable with natural materials

• They are usually made of a subwavelength (i.e. non-diffracting) periodic arrangement of resonating meta-atoms

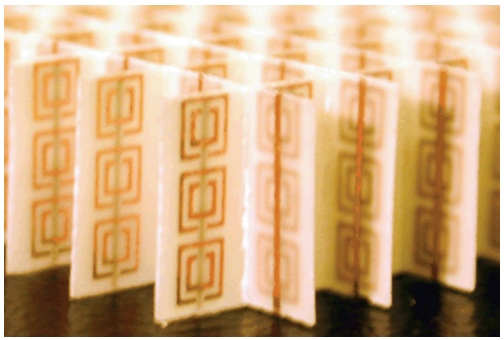


Adapted from M. Lapine et al. *IET Microw. Antennas Propagat.* **1**, 3-11 (2007)

Why the Use of Metamaterials

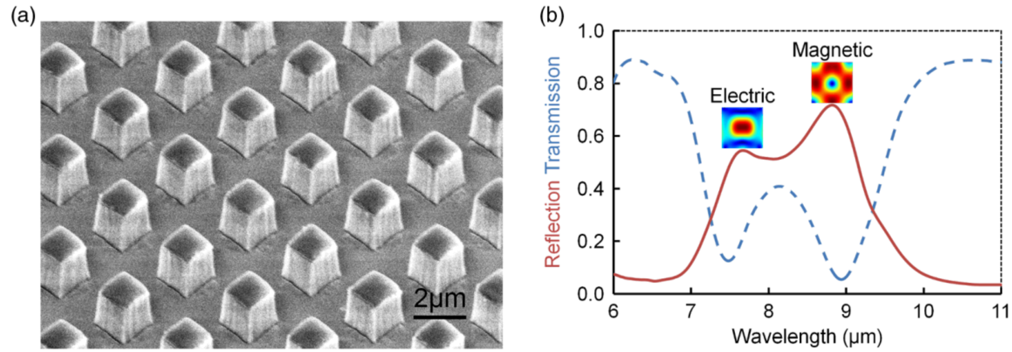
- Some of the interesting phenomena that can be attained through the use of metamaterials:

Negative refraction



R. A. Shelby et al. *Science* **292**, 77 (2001)

Artificial magnetism

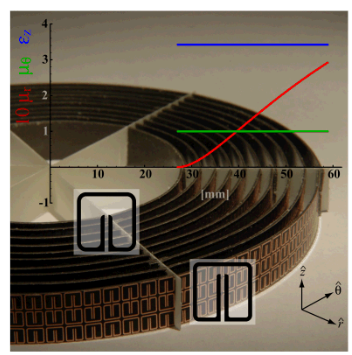


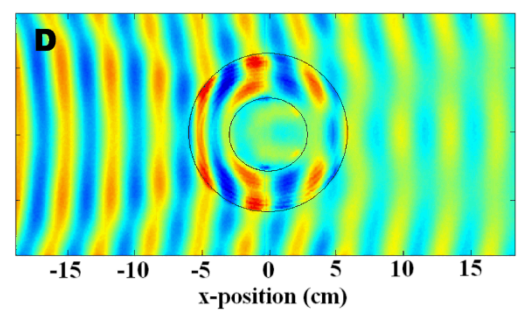
J. Ginn et al. *PRL* **108**, 097402 (2012)

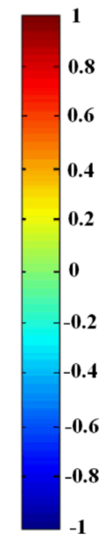
Super resolution

N. Fang et al. *Science* **308**, 534 (2005)

Cloaking

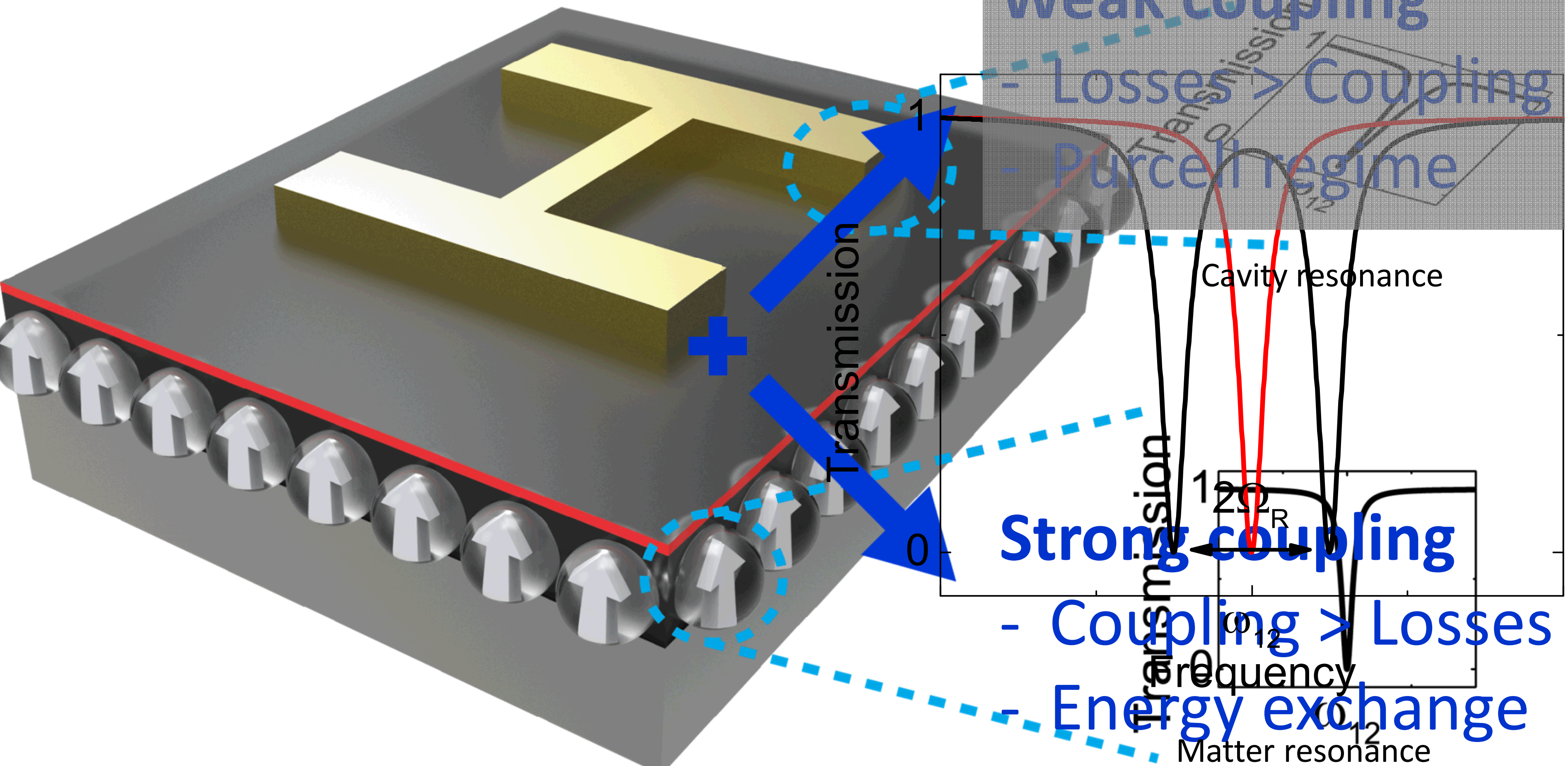






D. Schurig et al. *Science* **314**, 977 (2006)

Light-Matter Coupling in Metasurfaces Coupled to ISTs in QWs



Weak coupling
- Losses > Coupling
- Purcell regime

Strong coupling
- Coupling > Losses
- Energy exchange
- Rabi frequency

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

Applications of Strong Coupling Between Metasurfaces and ISTs

- Range of operation from near- to far-infrared: Frequency can be engineered by proper design of quantum wells and resonators
  - Design tunable optoelectronic devices (e.g. filters[1])
  - Enable incoherent and efficient light emission (i.e. "intersubband LEDs")[2]
  - Enable efficient nonlinear properties[3-5]

[1]Benz et al., Appl. Phys. Lett. **103**, 263116 (2013)

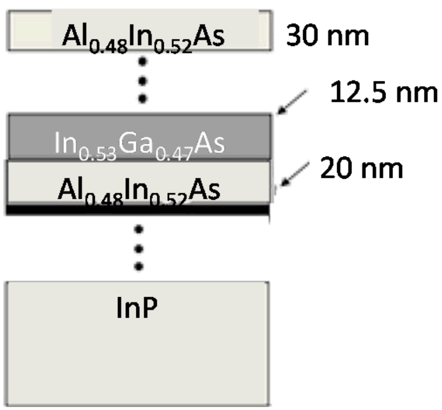
[2]Geiser et al. *Appl. Phys. Lett.* **101**, 141118 (2012)

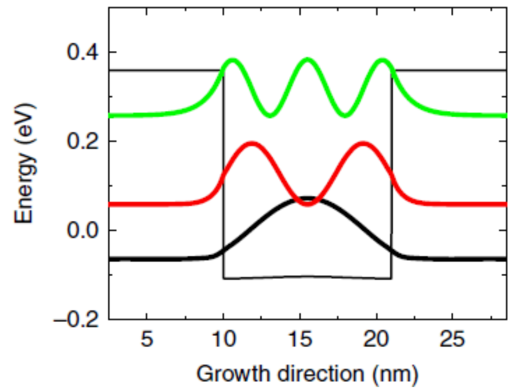
[3]Campione et al. *Appl. Phys. Lett.* **104**, 131104 (2014)

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

[5]Wolf*, Campione*, et al. *Nature Commun.* **6**, 7667 (2015)

Material Resonance: ISTs in QWs





- Stack of different semiconductors
- Quantized energy level designed
- Narrow absorption
- Promising for tuning from depletion

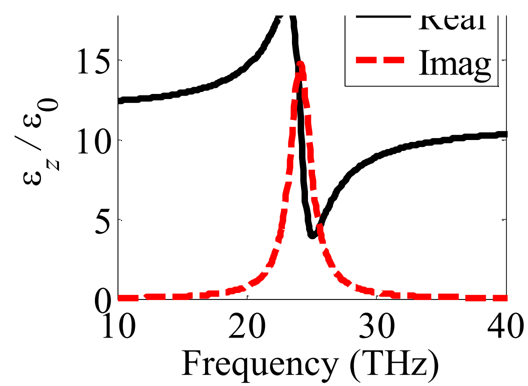
Benz et al., Appl. Phys. Lett. **103**, 263116 (2013)

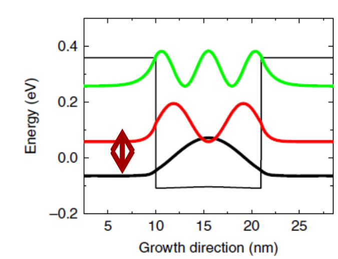
Only z polarized light can interact with the QWs and excite the optically active transition

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

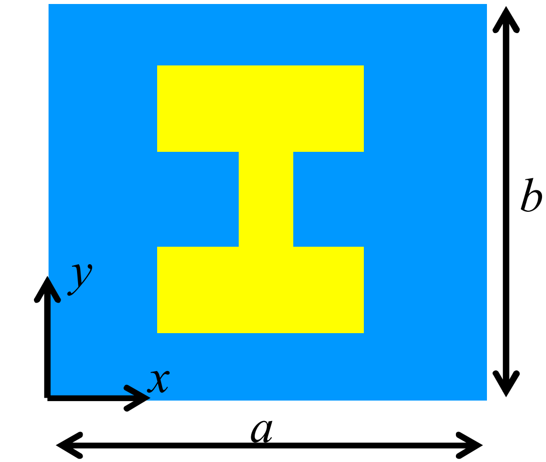
$$\varepsilon_z = \varepsilon_b + \chi \qquad \varepsilon_b = 11\varepsilon_0$$

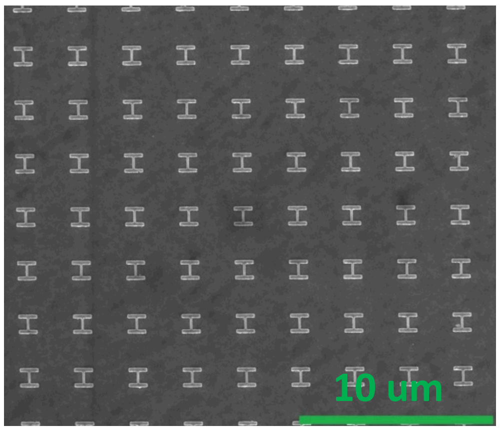
$$\chi = \frac{Ne^2}{m^*} f \frac{1}{\omega_0^2 - \omega^2 - 2i\gamma\omega}$$

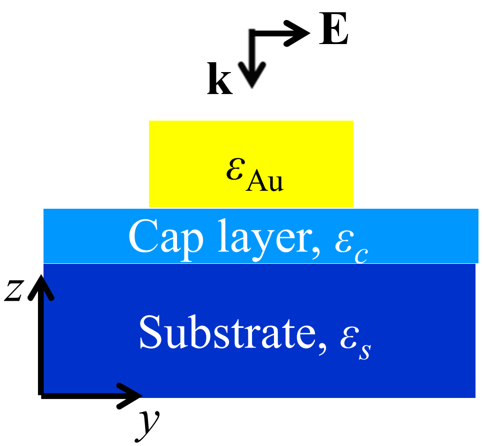


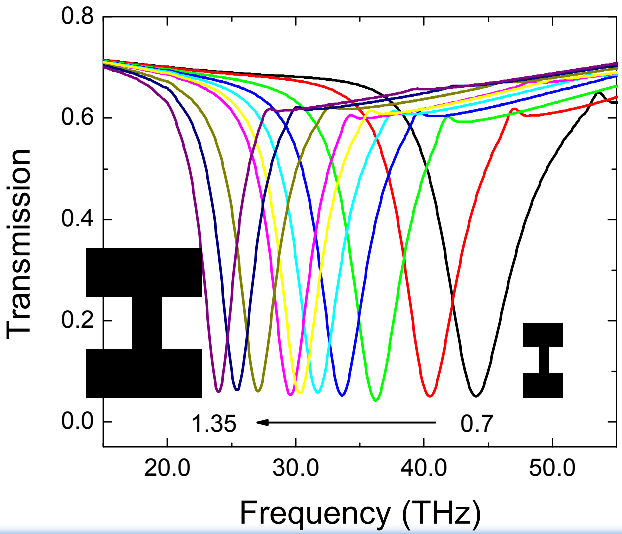


Optical Cavity Resonance: Metasurface









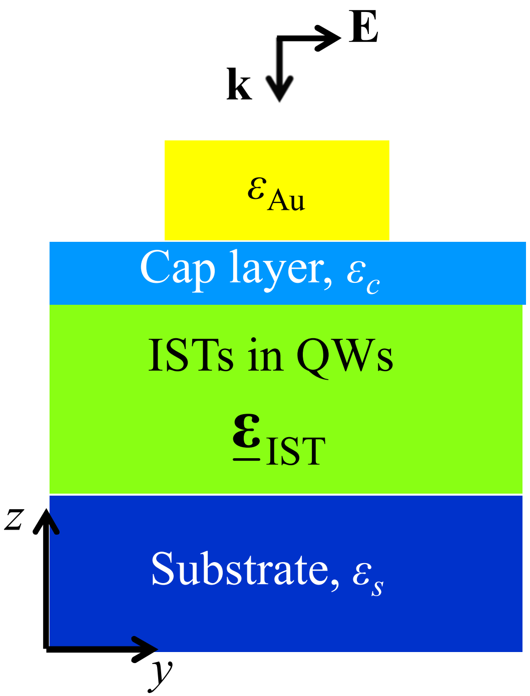
We thus pattern a metasurface of metallic resonators for two reasons:

1) Introduce the cavity resonance (dependent on materials, dimensions, etc.)

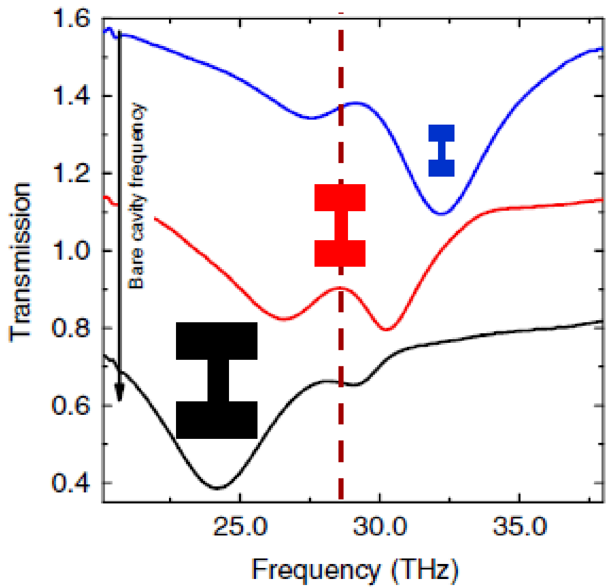
2) Produce strong z-polarized near fields to excite the ISTs and promote electrons in subbands

Spectral Properties

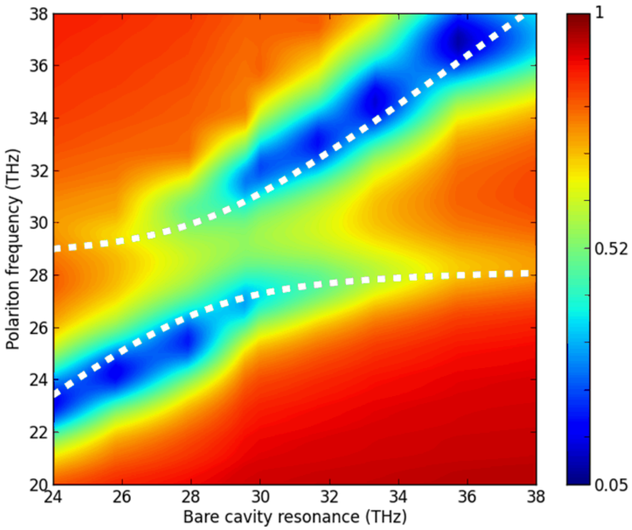
- z-polarized near fields excite the ISTs, inducing a splitting of 3.5 THz splitting



IST resonance



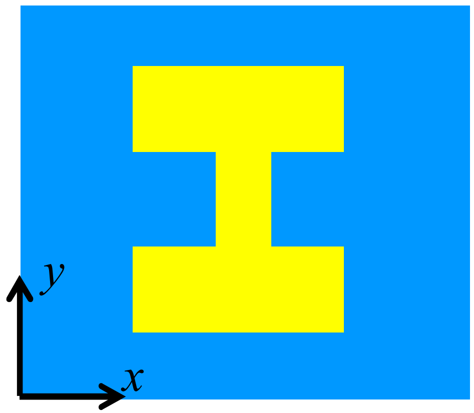
Full-wave

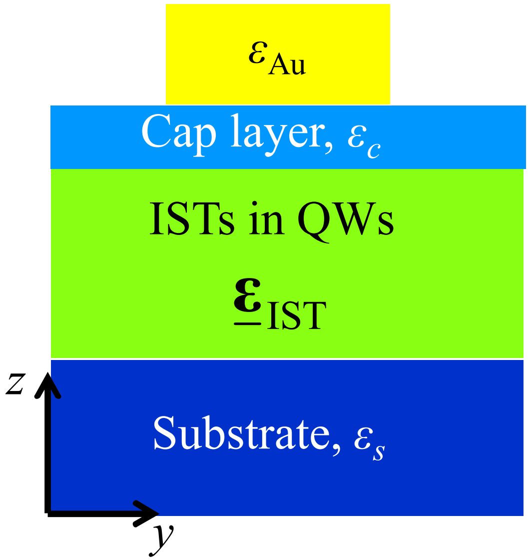


Benz et al., Nat. Commun. **4**, 2882 (2013)

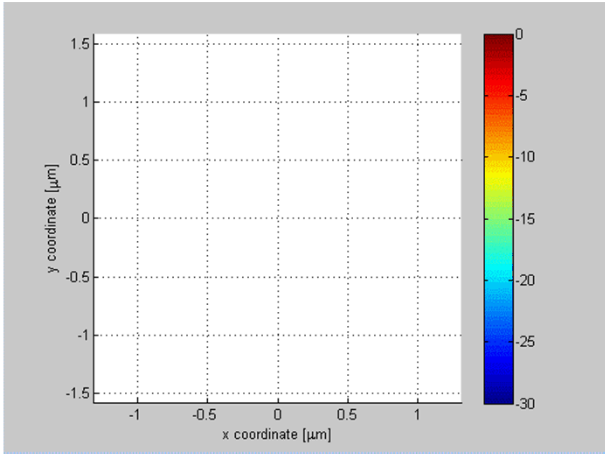
Validation of Energy Exchange

- The validation of energy exchange is provided through the following video



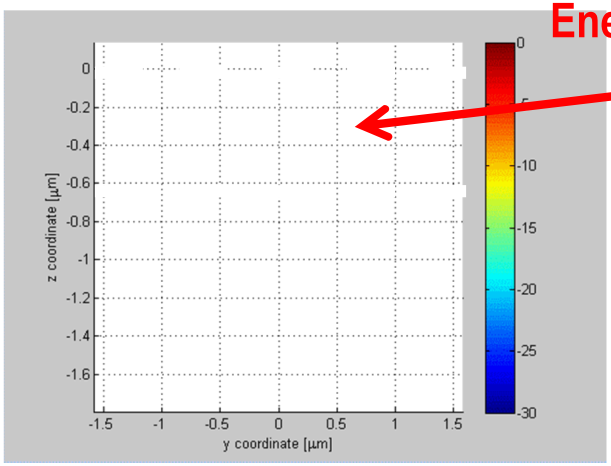


$|E_z|$



x-y plane

Energy exchange



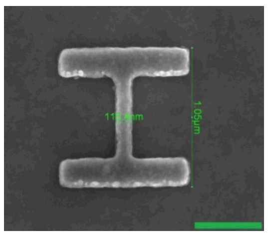
y-z plane

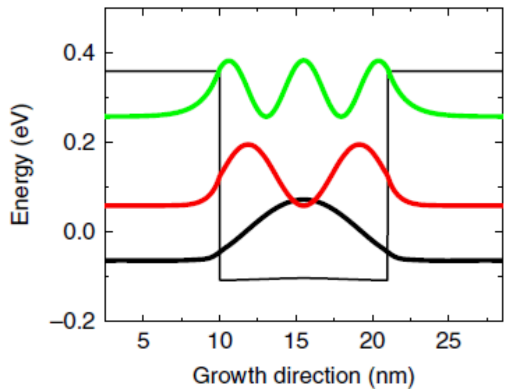
- Note that after the input pulse has gone through the structure, the Rabi oscillation is clearly visible

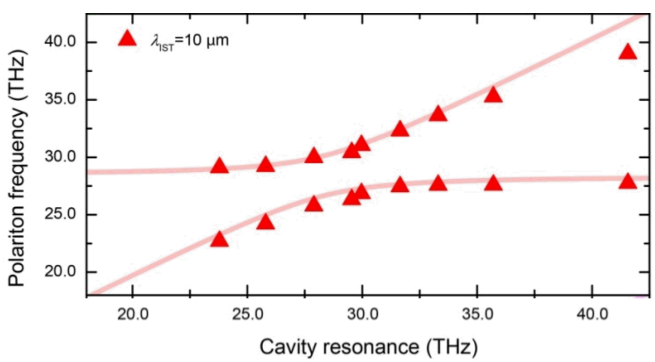
Strong Coupling: From mid-IR to near-IR

InGaAs QWs **(mid IR)**

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

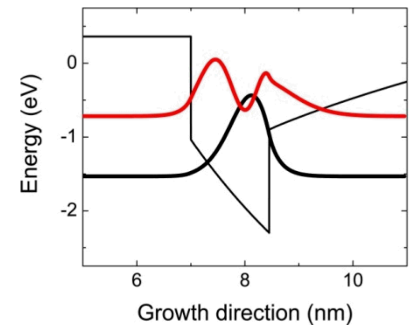


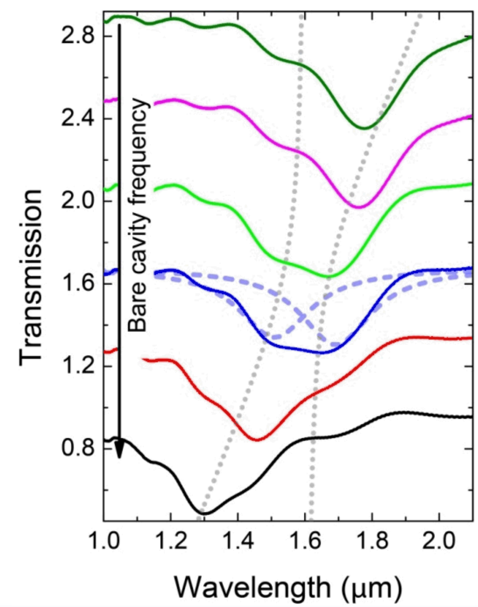




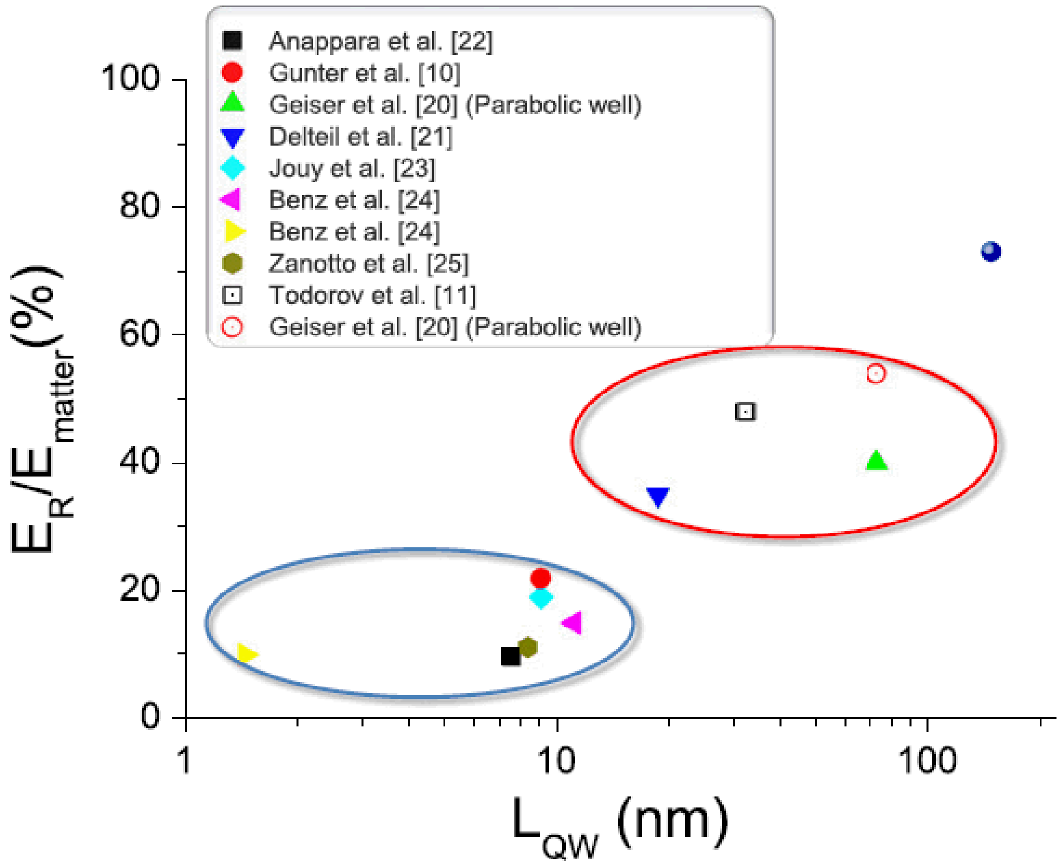
GaN QWs **(near IR)**

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





How Does the Resonator Design Affect the Rabi Splitting?



Askenazi et al. *New J. Phys.* **16**, 043029 (2014)

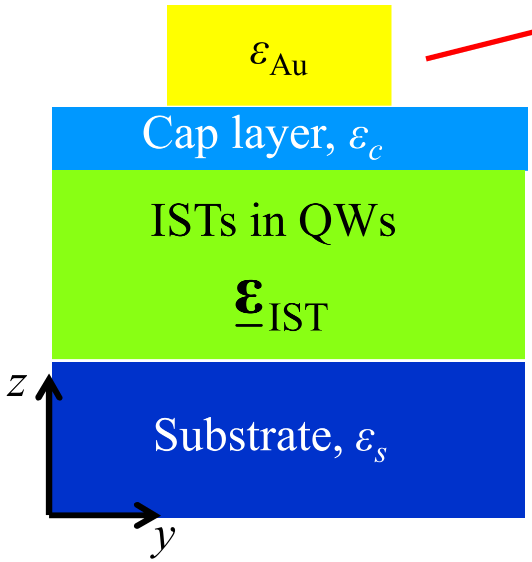
- Different resonator geometries may lead to different Rabi splittings
  - Even for similar QW lengths

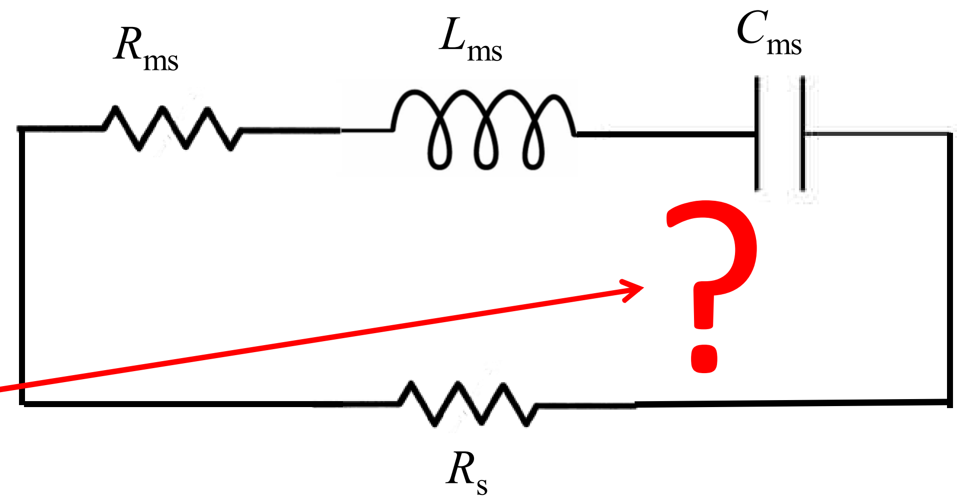
Maissen et al. , Proc. SPIE **8623**, 86231M (2013)

Campione et al., Phys. Rev. B **89**, 165133 (2014)

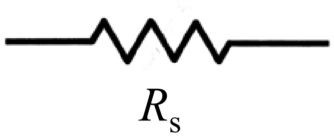
Modeling: Introduction of a Circuit Model

- A metasurface resonance can be modeled through a series RLC circuit



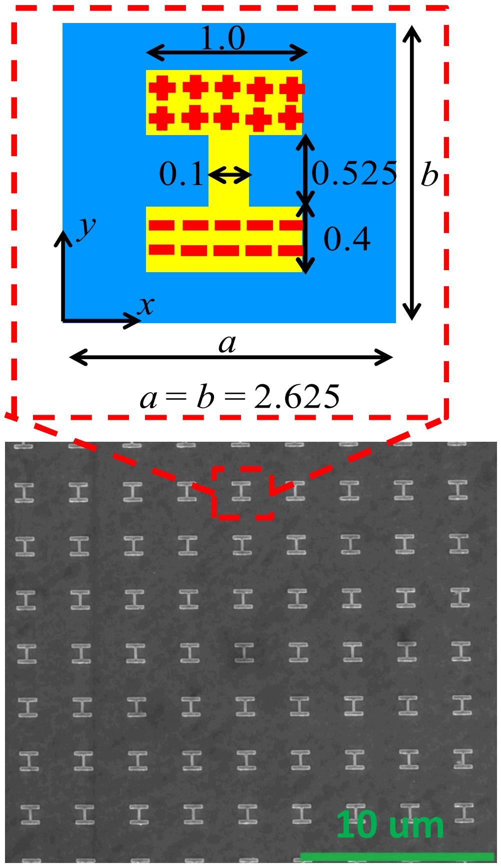


- Proper connection in absence of strong coupling, i.e. in absence of QWs in the semiconductor heterostructure
  - How can I model the contribution of the ISTs?



- The plane wave in the substrate can be modeled through a resistive load

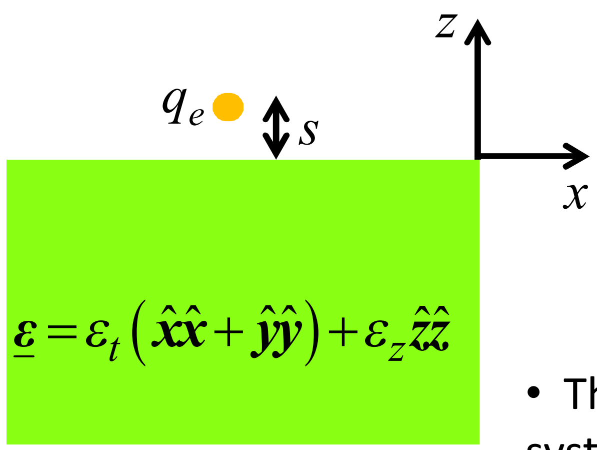
Electrostatic Approximation for Near Fields – IST Dipole Rule



- The ISTs selection rule requires z polarized electric fields
- z polarized electric fields are confined in the near fields of the resonators
- Near fields can be described resorting to the electrostatic approximation

Capacitance of a Static Dipole Over an Anisotropic Half Space

Campione et al., Phys. Rev. B **89**, 165133 (2014)



- We can estimate the electric potential of a charge

$$\phi_e = \phi_e(\varepsilon_t, \varepsilon_z)$$

- This lets us characterize the electrostatic fields of a two-charge system

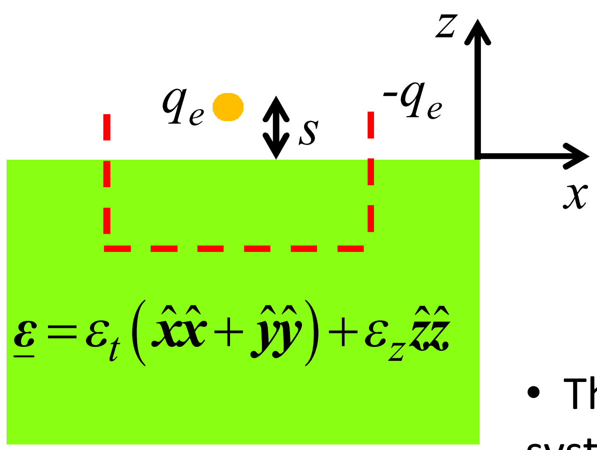
$$C = \frac{q_e}{\phi_+ - \phi_-} = \frac{\sqrt{\varepsilon_t \varepsilon_z} + 1}{\varepsilon_t + 1} C_{\mathrm{ms}} = C_{\mathrm{ms}} + C_{\mathrm{eq}}^{\mathrm{IST}} = \xi C_{\mathrm{ms}}$$

C_{ms}: MS capacitance when $\varepsilon_z = \varepsilon_t$ ξ: coupling coefficient

$C_{\mathrm{eq}}^{\mathrm{IST}} = C_{\mathrm{ms}}\left(\sqrt{\varepsilon_t \varepsilon_z} - \varepsilon_t\right) / (\varepsilon_t + 1)$: capacitor representing the strong coupling to the ISTs

Capacitance of a Static Dipole Over an Anisotropic Half Space

Campione et al., Phys. Rev. B **89**, 165133 (2014)



- We can estimate the electric potential of a charge

$$\phi_e = \phi_e(\varepsilon_t, \varepsilon_z)$$

- This lets us characterize the electrostatic fields of a two-charge system

This capacitor is a measure of the near-field interaction between dipole and the ISTs

C_{ms}: MS capacitance when $\varepsilon_z = \varepsilon_t$ $\qquad$ ξ: coupling coefficient

$C_{\mathrm{eq}}^{\mathrm{IST}} = C_{\mathrm{ms}}\left(\sqrt{\varepsilon_t \varepsilon_z} - \varepsilon_t\right) / (\varepsilon_t + 1)$: capacitor representing the strong coupling to the ISTs

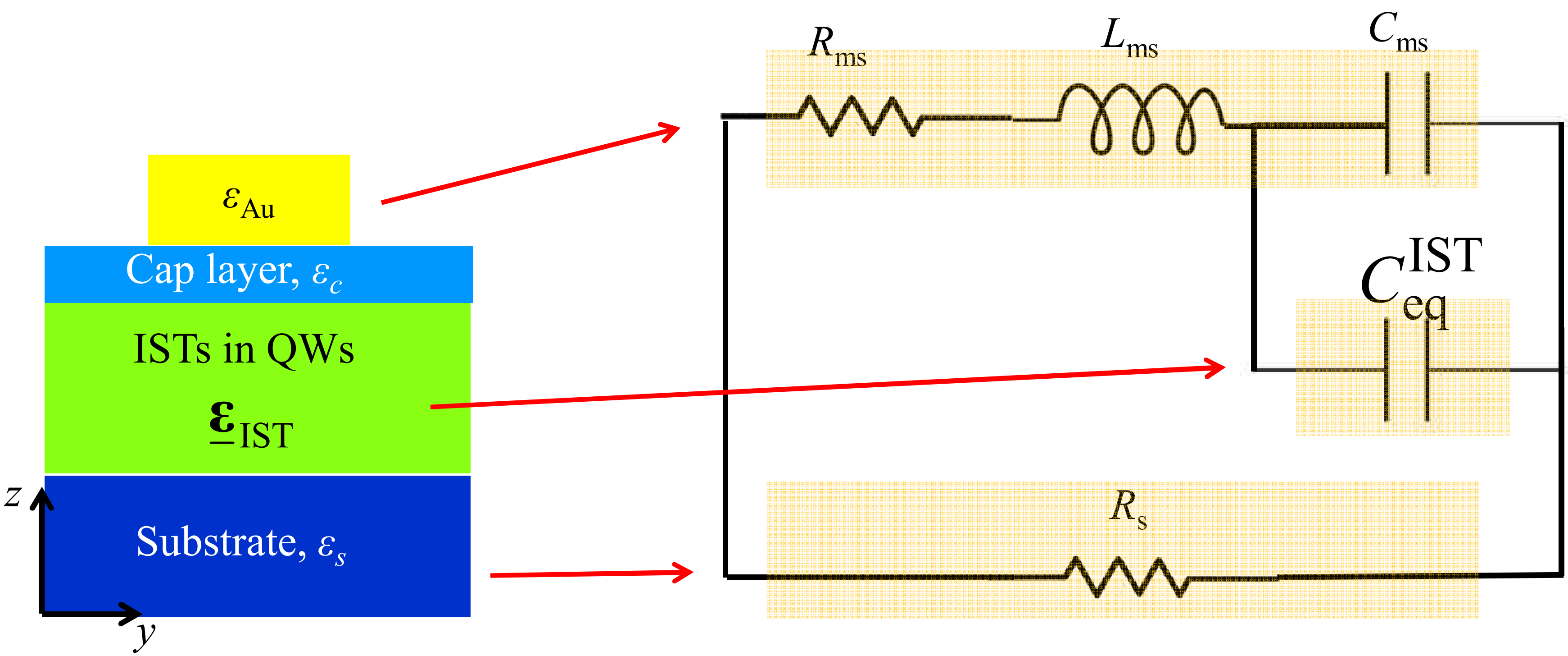
Strong Coupling Capacitor in Place in the Circuit Model

- The total capacitor is thus the sum of two contributions

$$C = C_{\text{ms}} + C_{\text{eq}}^{\text{IST}}$$

- The IST capacitor is obtained using
- Computational model of QWs using full-wave and circuit simulations

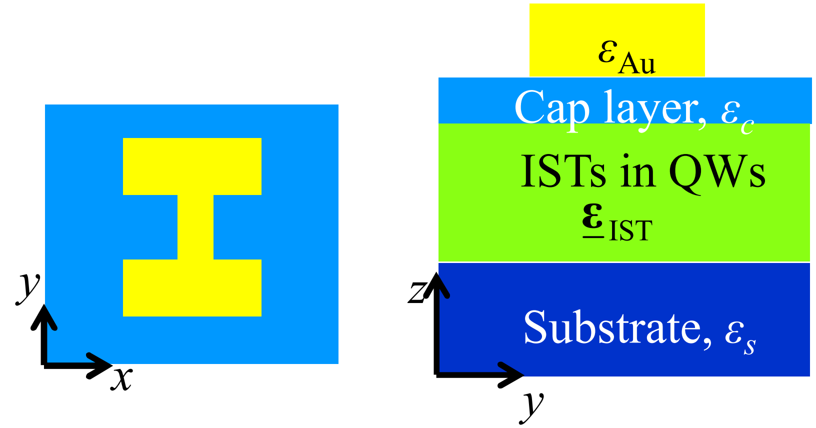
$$C_{\text{eq}}^{\text{IST}} = C_{\text{ms}}\left(\sqrt{\varepsilon_t \varepsilon_z} - \varepsilon_t\right) \Big/ \left(\varepsilon_t + 1\right)$$

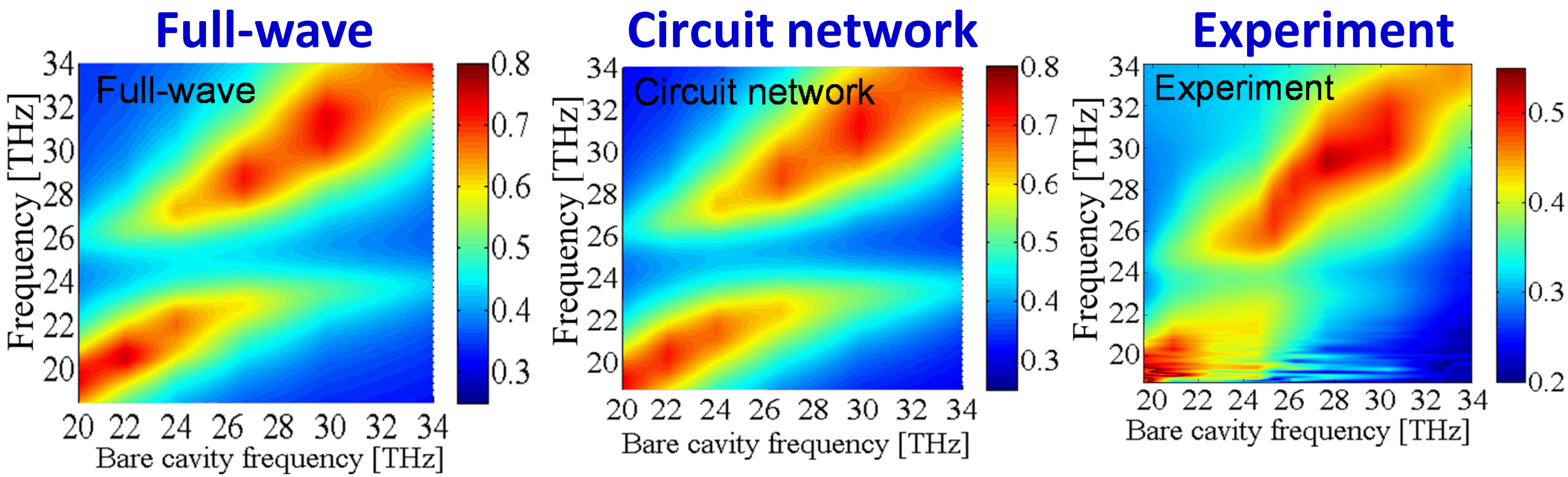


Validation of the Circuit Model: Spectral Properties

Campione et al., Phys. Rev. B **89**, 165133 (2014)

Reflectivity $|\Gamma|^2$

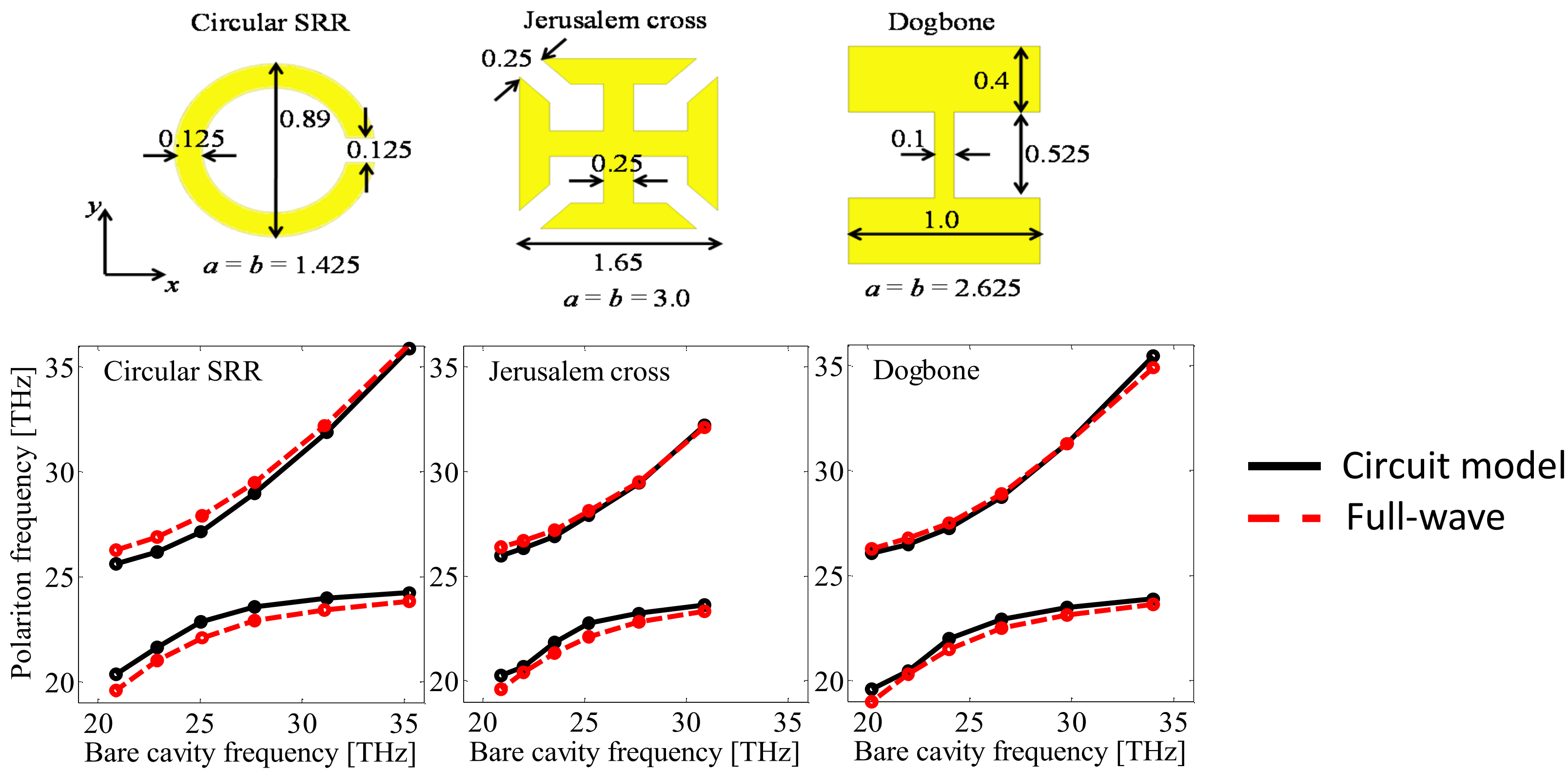




Not only do we recover the resonance frequency locations, but we are also able to quantify the magnitude of reflectivity

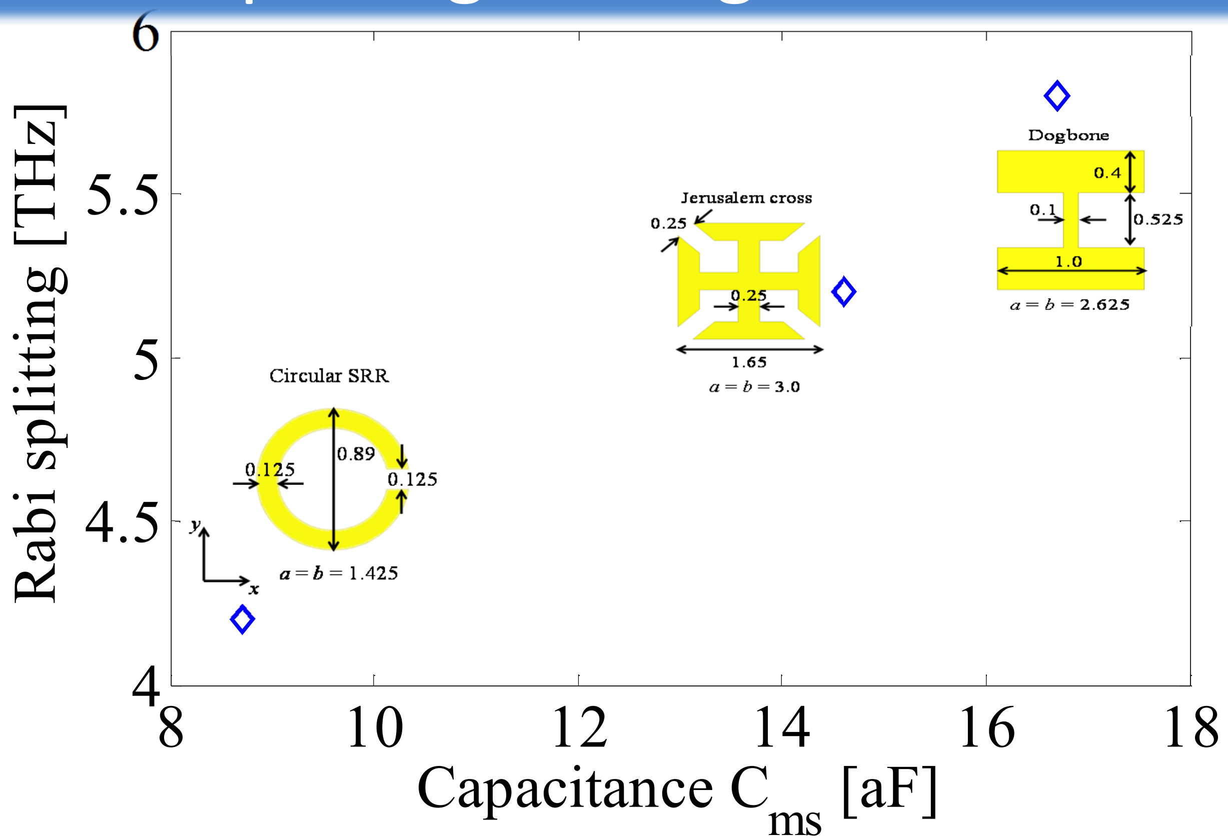
Circuit Model: How to Maximize Rabi Splitting

- We now investigate different resonators on top of the same quantum well



- Note the good agreement with full-wave simulations (red dashed)
- Note the narrower splitting for SRR resonator

Circuit Model: How to Maximize Rabi Splitting – Design Guidelines



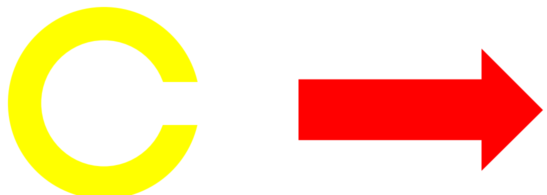
Campione et al., Phys. Rev. B **89**, 165133 (2014)

Benz, Campione, et al., Nano Lett. **15**, 1959 (2015)

To increase the Rabi splitting the metasurface should exhibit a larger capacitance

Another Example: Split Ring Resonators

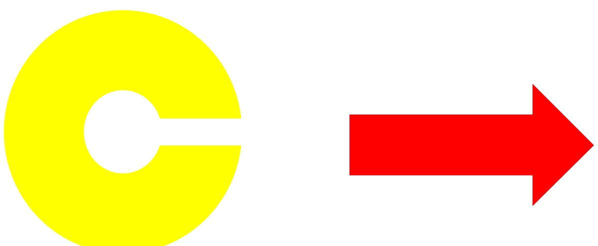
- Let's take the SRR geometry of the previous slide



$C_{ms} = 8.7$ aF

Splitting = 4.2 THz

- To increase its capacitance, we increase the metal traces



$C_{ms} = 13.7$ aF

Splitting = 4.8 THz

A larger capacitance corresponds to a larger Rabi splitting

- Dependence with resonator physical dimensions:

$$C_{gap} = \varepsilon_0 hw/g + \varepsilon_0 \left(h + w + g\right)$$

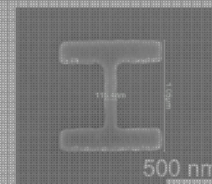
$$C_{SRR} = C_{gap} + C_{surf}$$

$$C_{surf} = \left[2\varepsilon_0 \left(h + w\right)\log\left(4R / g\right)\right] / \pi$$

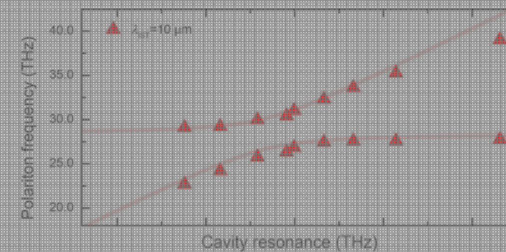
Sydoruk et al., J. Appl. Phys. **105**, 014903 (2009)

Outline of the Talk
Strong Light-Matter Interaction

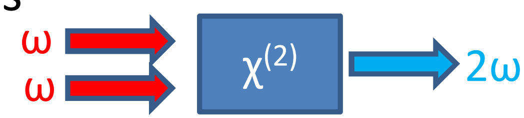
- Show how to use metamaterial nanoresonators to



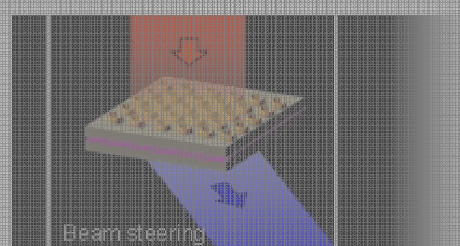
- Achieve strong coupling with intersubband transitions (ISTs) in quantum wells (QWs)



- Achieve efficient second harmonic (SH) generation in ISTs



- Form a metasurface for beam manipulation of the SH signal

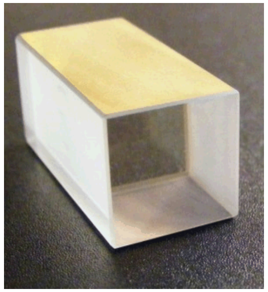


Second Harmonic Generation

- Strongly coupled structures exhibit large field enhancements – Useful to enhance second harmonic generation in ISTs in QWs

Conventional method:

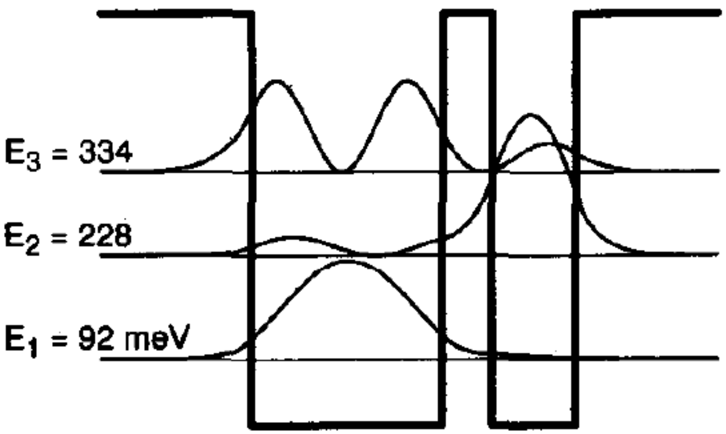
- macroscopic nonlinear crystal (BBO, $LiNbO_3$,…)
- Low efficiency → long path length → **phase matching is a problem**



The use of ultrathin metasurfaces that are free of phase-matching constraints could open up a plethora of applications, such as frequency up- and down-conversion and beam manipulation at the second harmonic frequency

Second Order Susceptibility in ISTs in QWs

- Asymmetric QWs may exhibit large second order susceptibility χ(2)



Typical values ~250000 pm/V

vs.

10s of pm/V for LiNbO3

Resonant process!

$$\chi^{(2)}(2\omega) = \frac{e^3}{\varepsilon_0} N \cdot \frac{\langle z_{12}\rangle\langle z_{23}\rangle\langle z_{31}\rangle}{(\hbar\omega - \Delta E_{12} - i\Gamma_{12})(2\hbar\omega - \Delta E_{13} - i\Gamma_{13})}$$

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

Design principles:

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

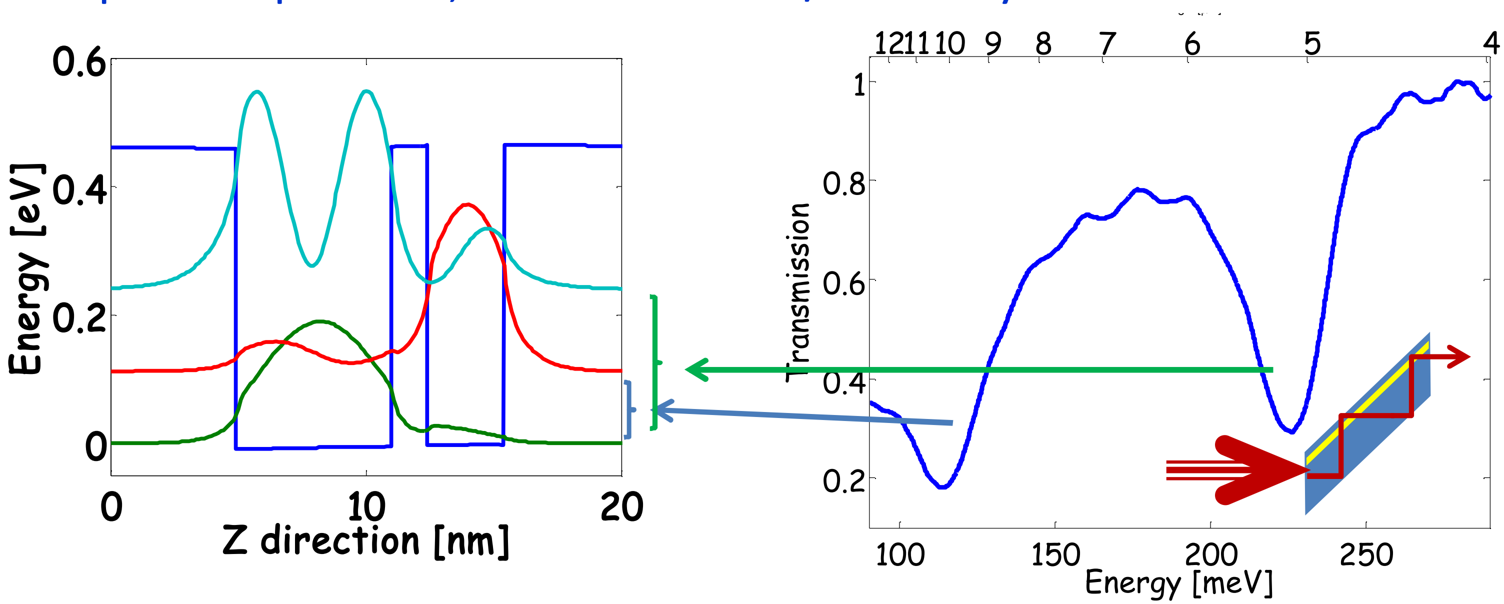
Rosencher et al. *Electron. Lett.* **25**, 1063 (1989) Capasso et al. *IEEE J. Quantum Electr.* **30**, 1313 (1994)
Khurgin *J. Opt. Soc. Am. B* **6**, 1673 (1989)

Design and Fabrication of ISTs

QW designed for 10μm → 5μm SHG, based on InGas/AlInAs system

$$\chi^{(2)} \propto N \cdot z_{12} z_{23} z_{13}$$

$$z_{ij} \propto \frac{\langle \Psi_i | \vec{P} | \Psi_j \rangle}{E_j - E_i}$$



3 levels are designed to create a $\chi(2)$

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

Wolf*, Campione*, et al. Nature Commun. **6**, 7667 (2015)

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

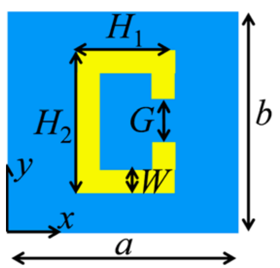
Second Harmonic Generation – Design of the Strong Coupling Structure

- Resonant metamaterials enhance second harmonic generation

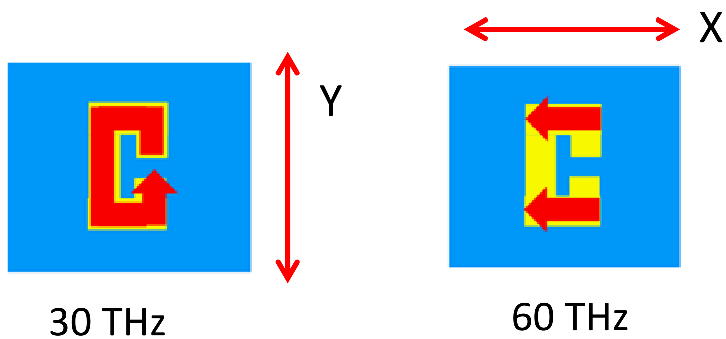
Gorkunov et al. *Appl. Phys. Lett.* **88**, 071912 (2006)
Klein et al. *Science* **313**, 502 (2006)
Kanazawa et al. *Appl. Phys. Lett.* **99**, 024101 (2011)
Thyagarajan et al. *Opt. Express* **20**, 12860 (2012)
Ginzburg et al. *ACS Photon.* **2**, 8 (2014)

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

Proposed design



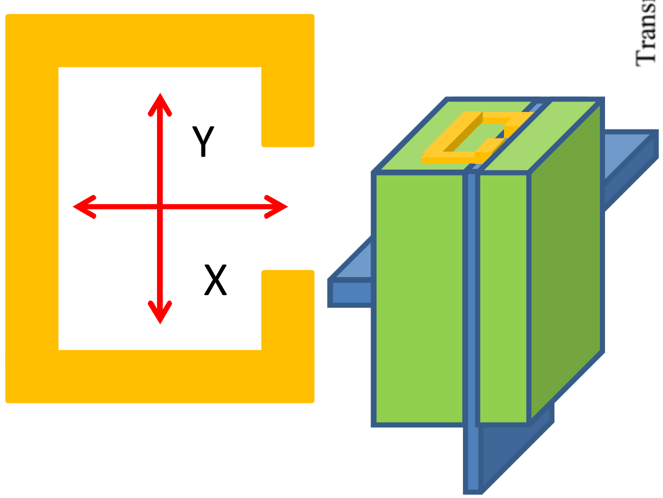
Supported resonances

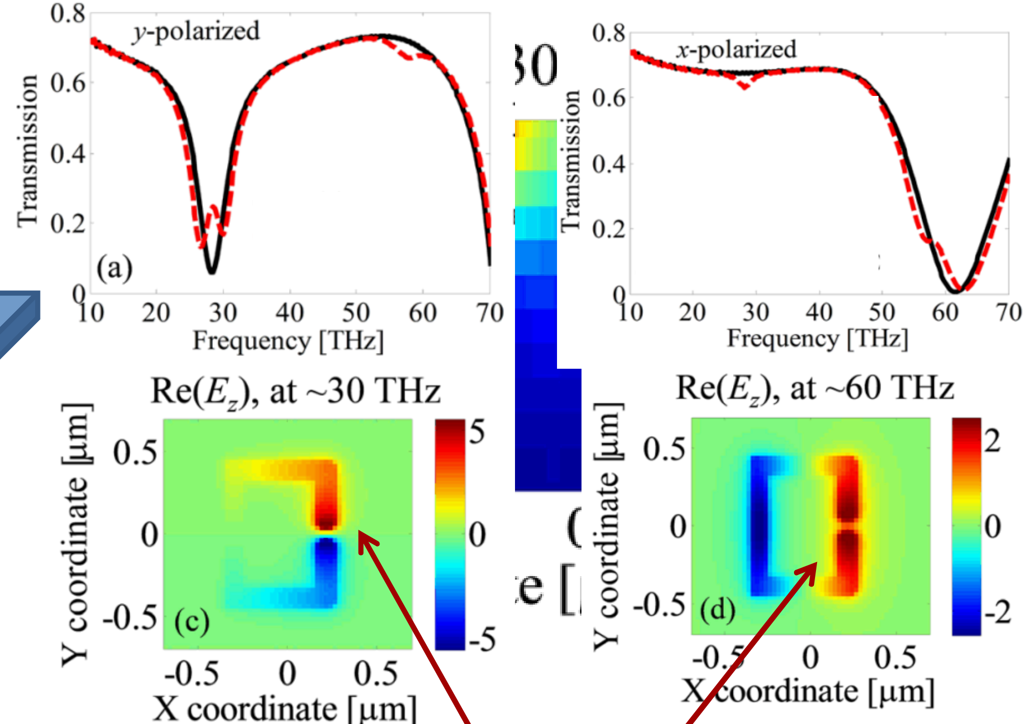


Campione et al. *Appl. Phys. Lett.* **104**, 131104 (2014)

Nanoresonators Enhance the Fields

- Metallic nanoresonators **have** E_z in near-field for normal incidence





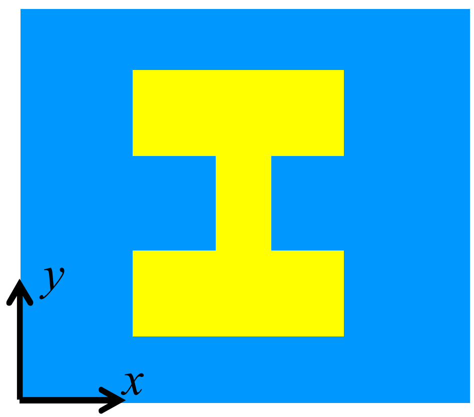
- Designed to have two resonances in FF and SH in cross polarizations
- Enhances fields by up to 5 times

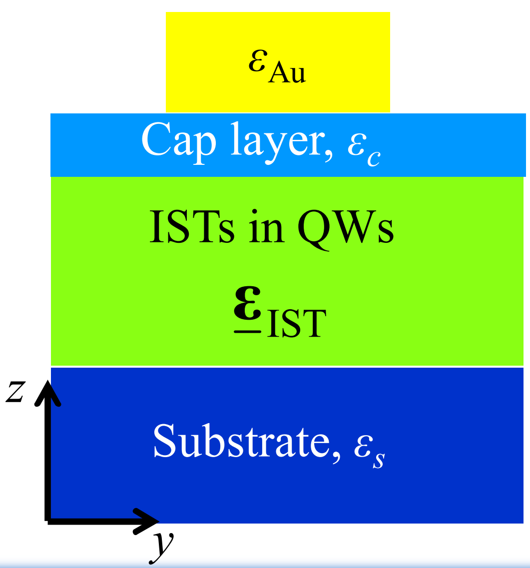
Good spatial field overlap!

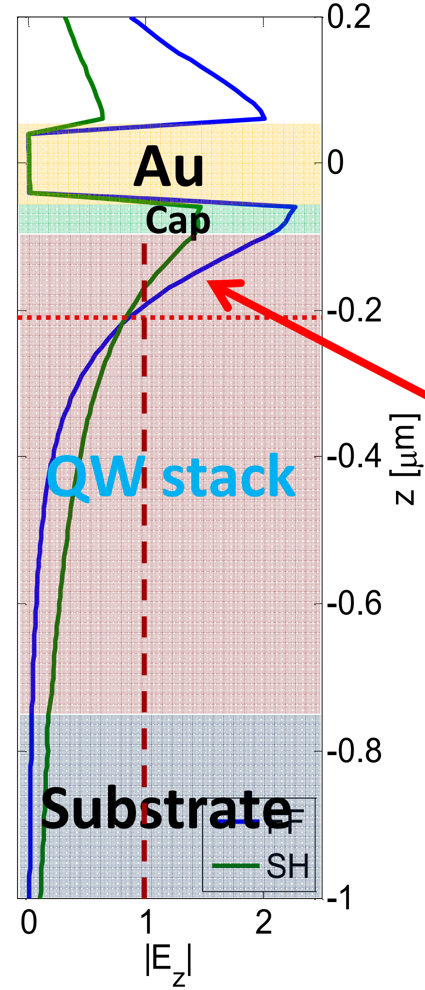
Campione et al. *Appl. Phys. Lett.* **104**, 131104 (2014).

Enhanced z-Polarized Fields Within QWs

- Good field overlap within the QWs

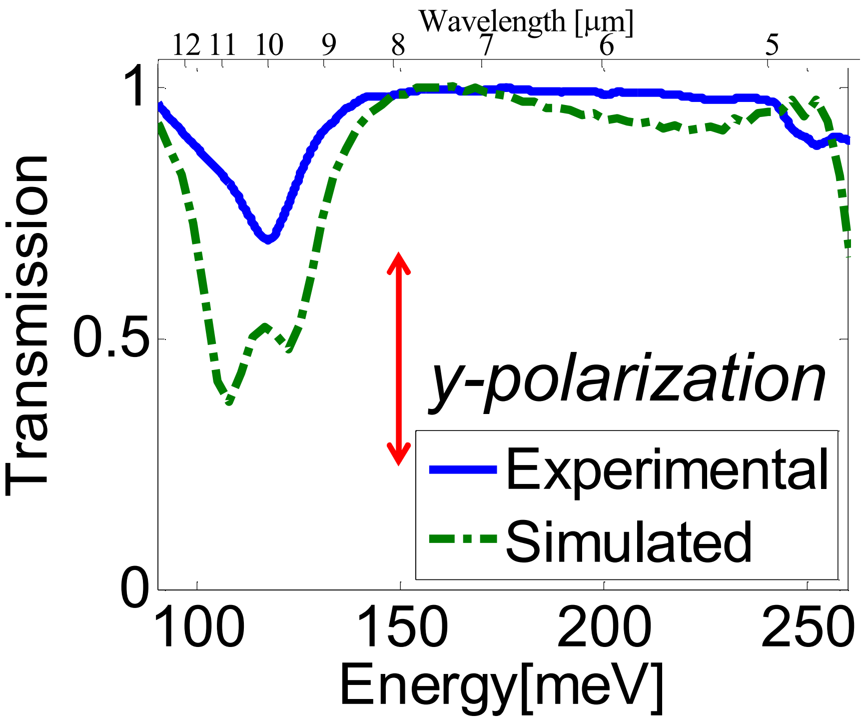


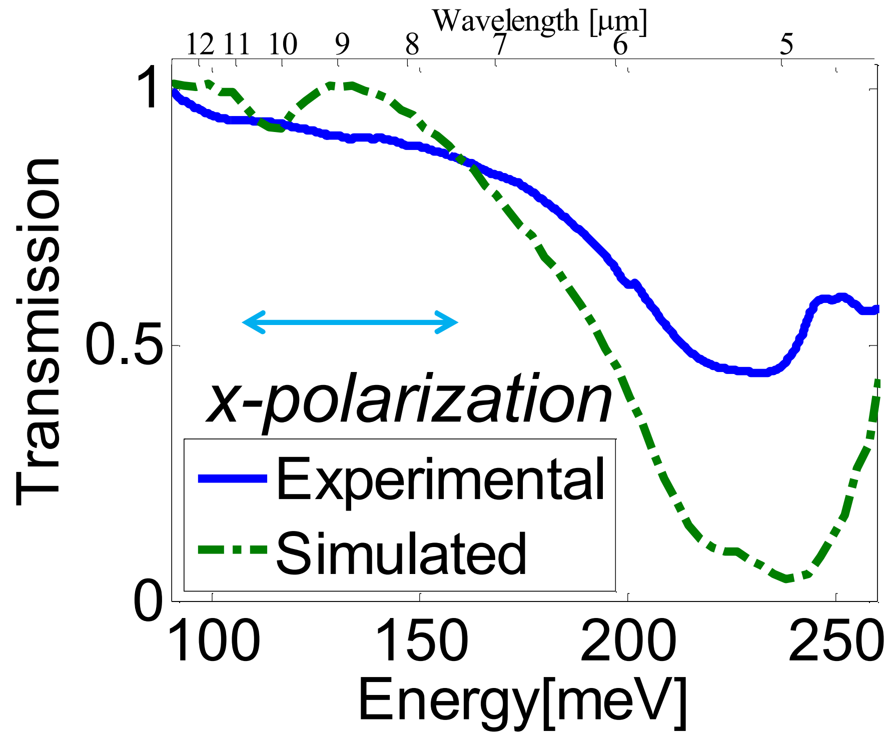


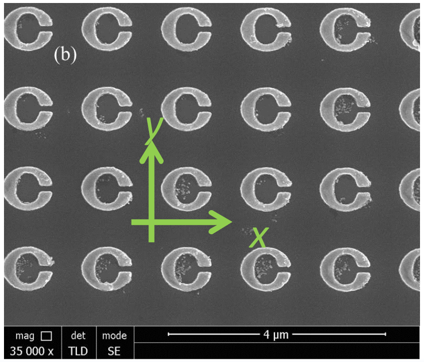


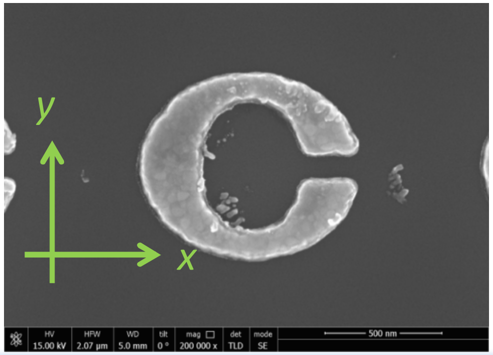
1) z-polarized field within the QWs
2) Enhanced with respect to $|E_y|$ of the plane wave

Linear Transmission: Simulation and Experimental Results

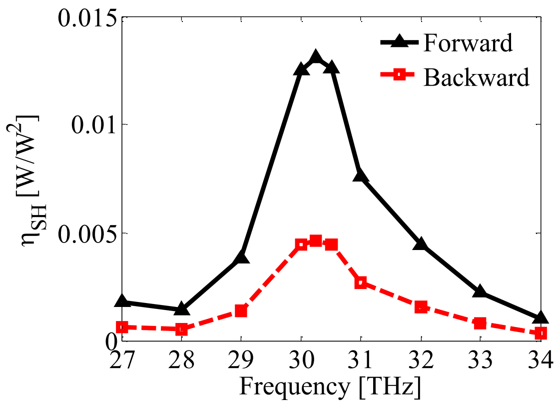








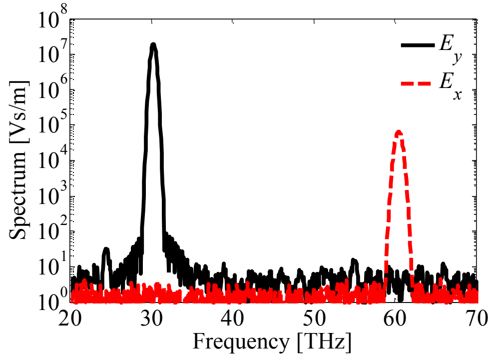
Second Harmonic Generation – Simulation Results



SH conversion efficiency $\eta_{SH}^{t,r} = P_{SH}^{t,r} / P_{FF}^2$

- An optimum value for the pump frequency that maximizes the SH conversion efficiency is found for reflected and transmitted pulses

  Maximum estimated efficiency: 10^{-2} W/W^2



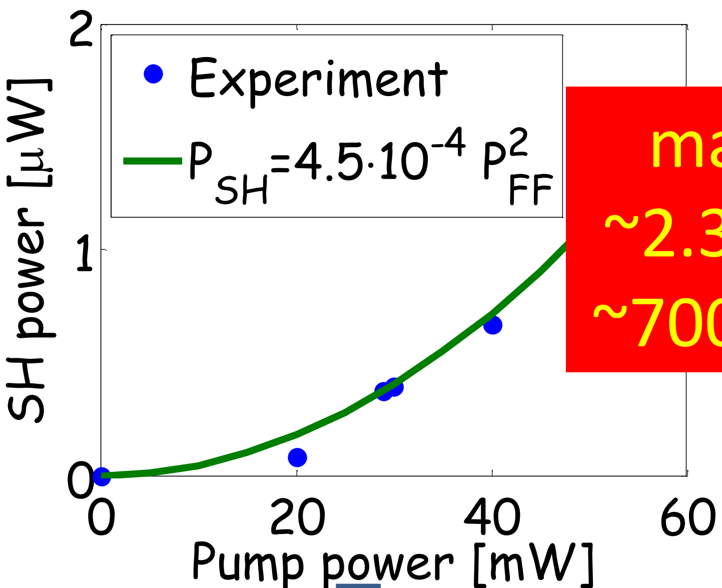
- SH signal is found in **perpendicular** polarization with respect to the pump polarization

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

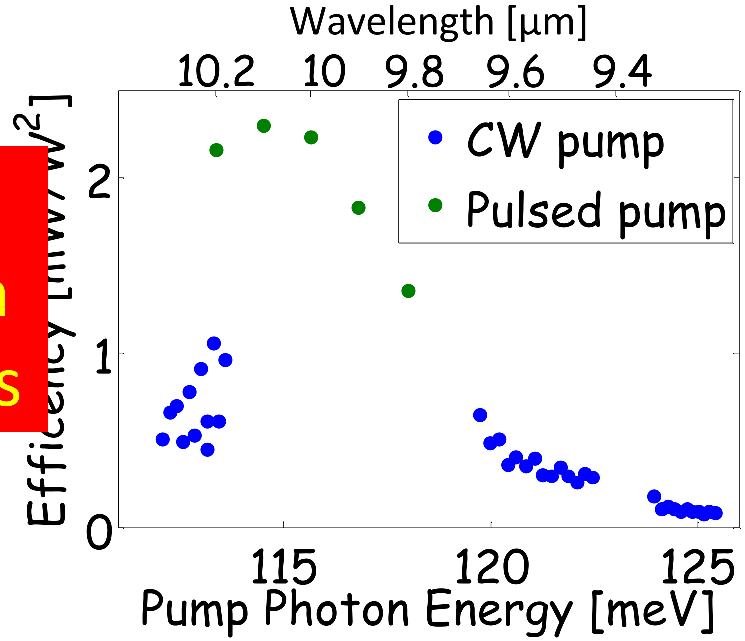
Power and Frequency Dependence of SH

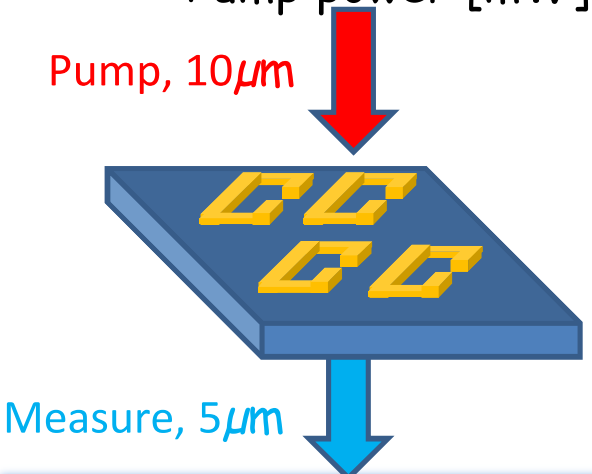
Sandia National Laboratories

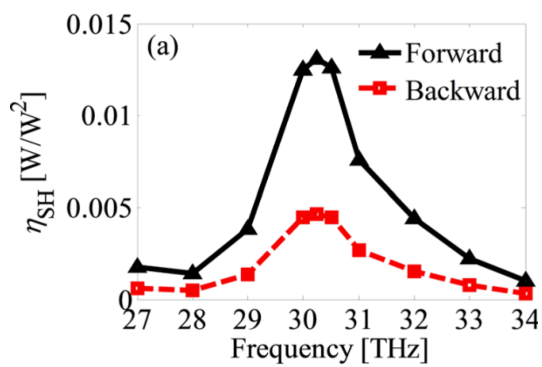
Pump is CW CO_2 laser



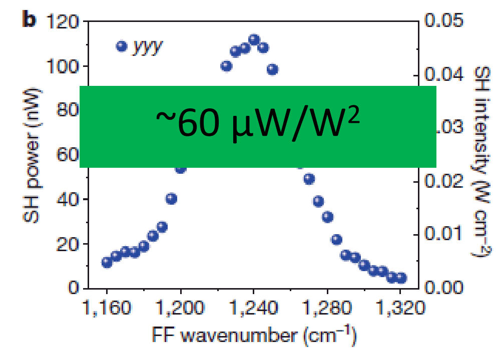
max efficiency:
~2.3 mW/W² with
~700 nm thickness







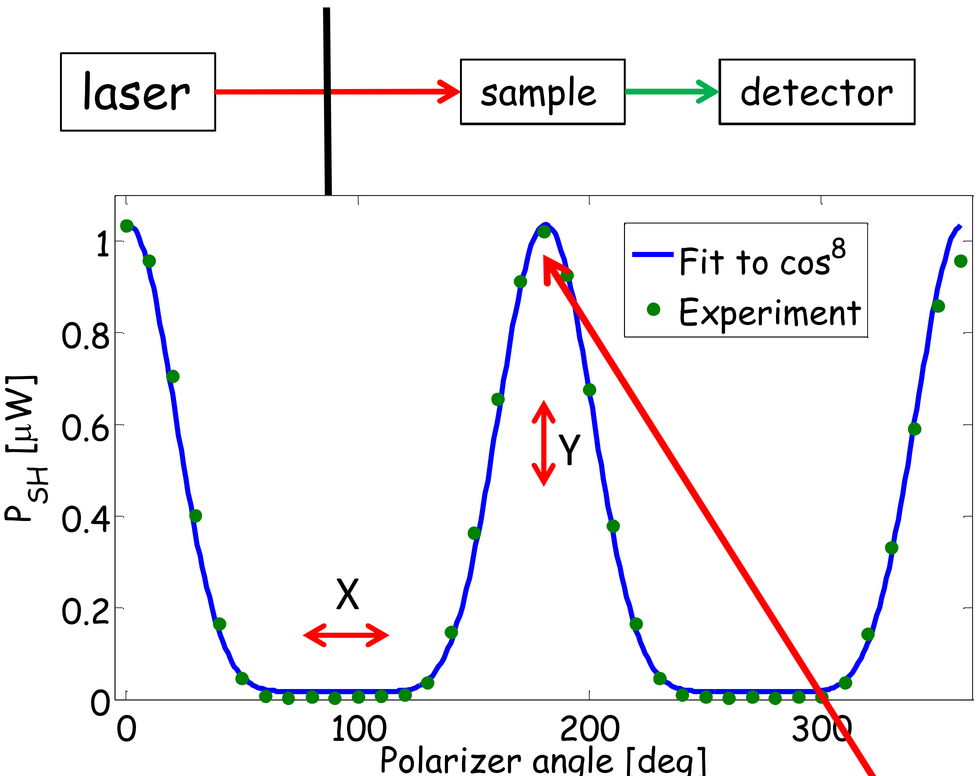
S. Campione et al. *Appl. Phys. Lett.* **104**, 131104 (2014)

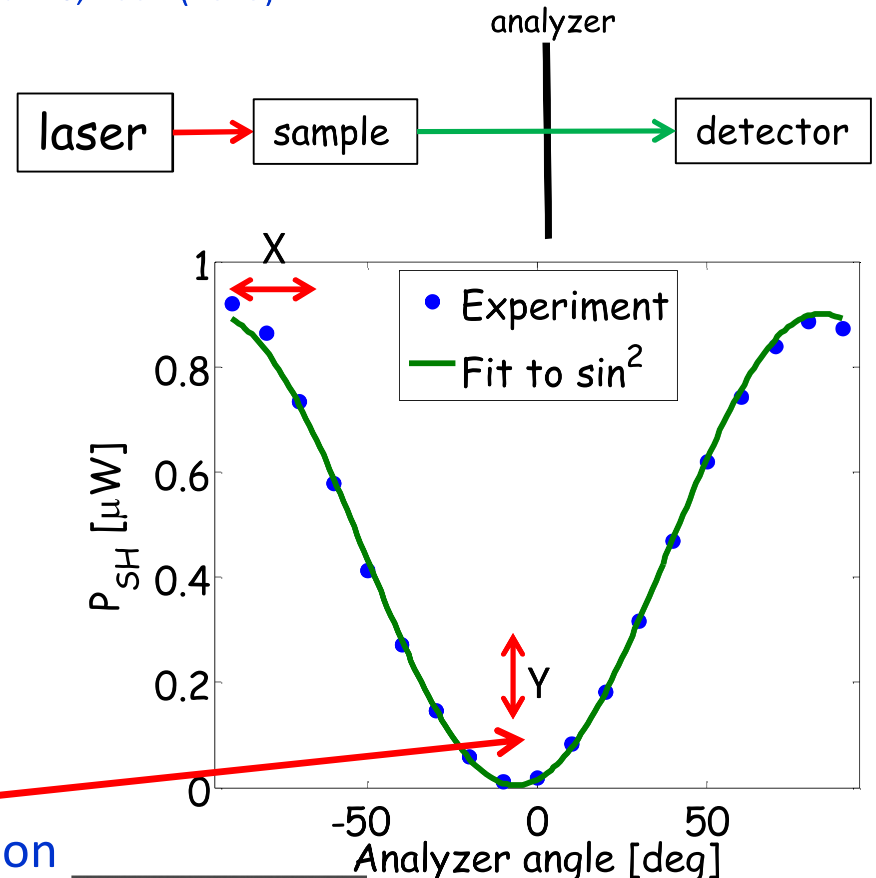


Lee et al. *Nature* **511**, 65-69 (2014)

Polarization Properties of SH

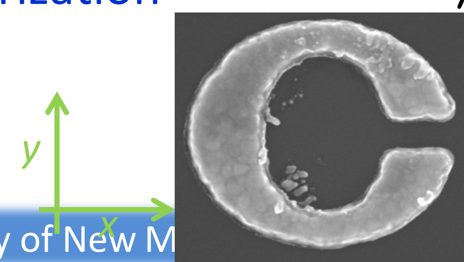
Wolf et al. Nature Commun. **6**, 7667 (2015)





laser polarization

in \ out	x	y
x	--	--
y	☺	--

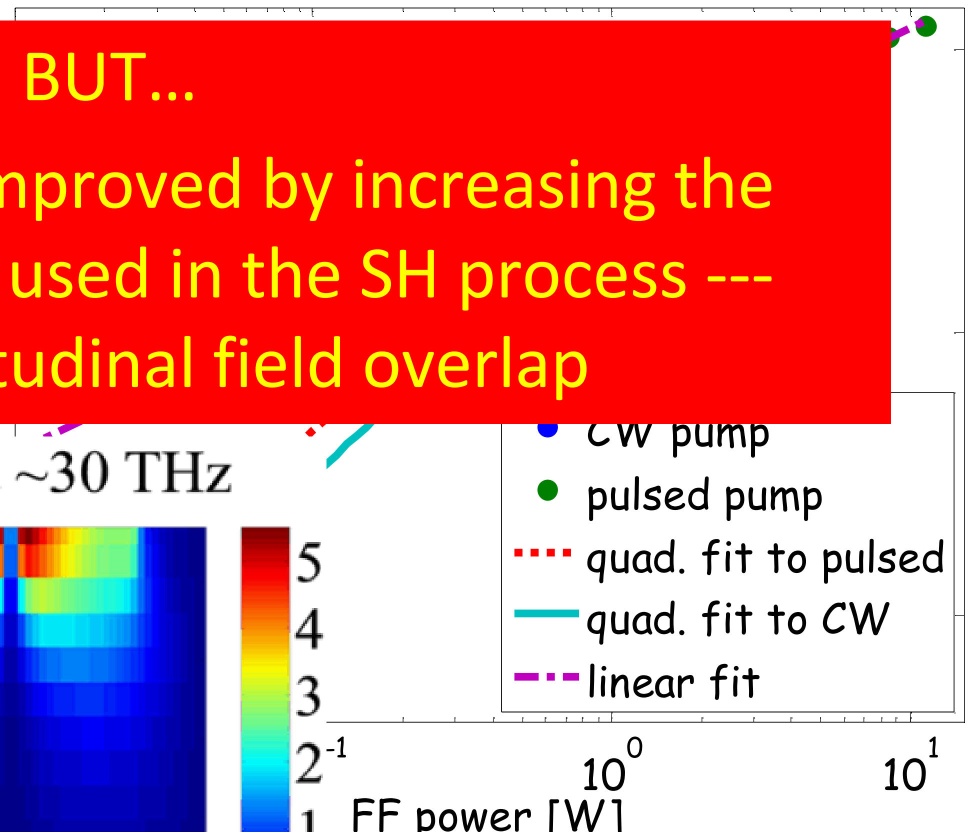


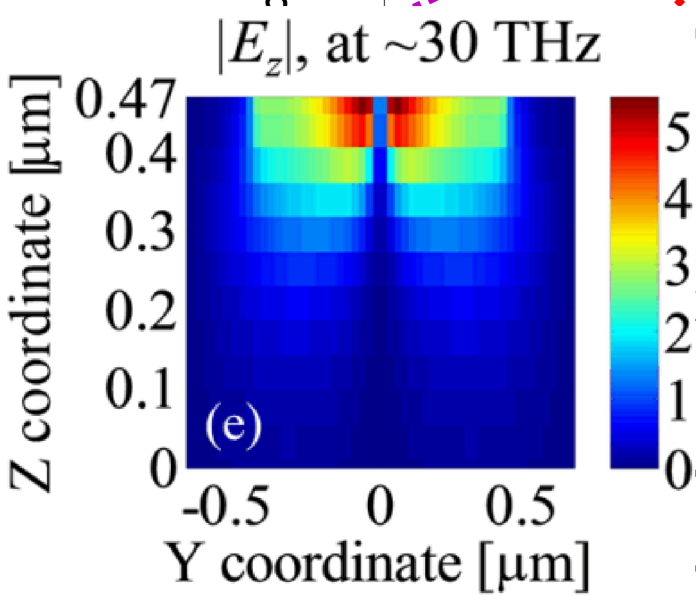
Saturation of the SH Process

- No C… effic… inte…
- CW … frequency
- 0.1% conversio… ~700nm path l…
- Due to IST's ab… saturation

BUT…

Results could be improved by increasing the volume of QW IST used in the SH process --- Better longitudinal field overlap



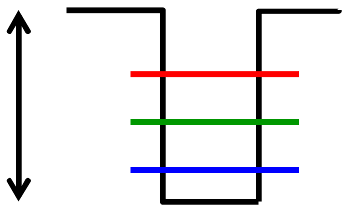


…version: ~0.1%

~6kW/cm^2

Moving to Shorter Wavelengths

Conduction band offset



Challenges:

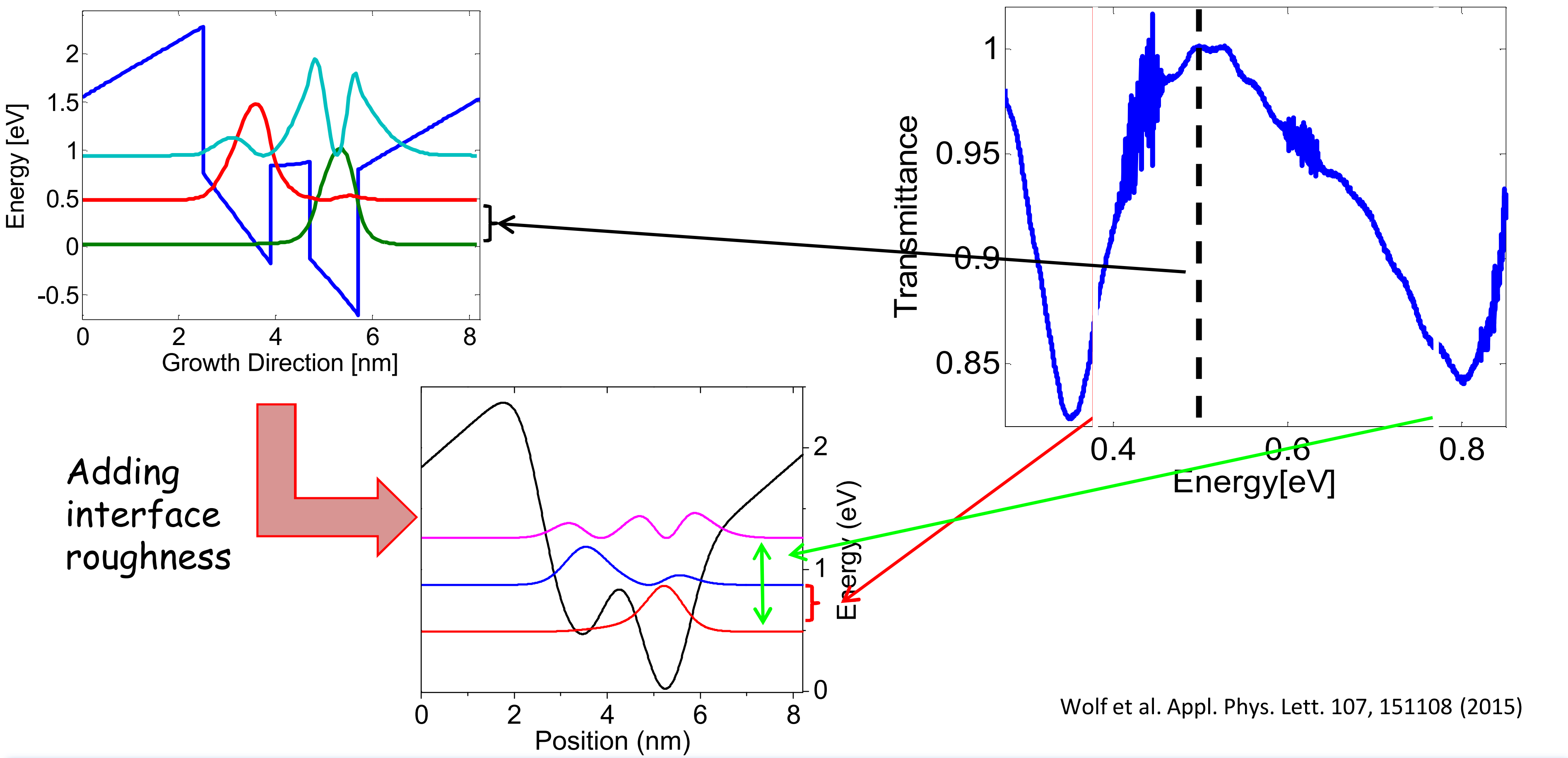
– Very large CB offset required → III-Nitrides are hard to control

– Resonators dimensions shrink → fabrication approaches the limit of conventional EBL

– Metal losses increase → will strong coupling prevail??

SHG in III-Nitride ISTs in QWs

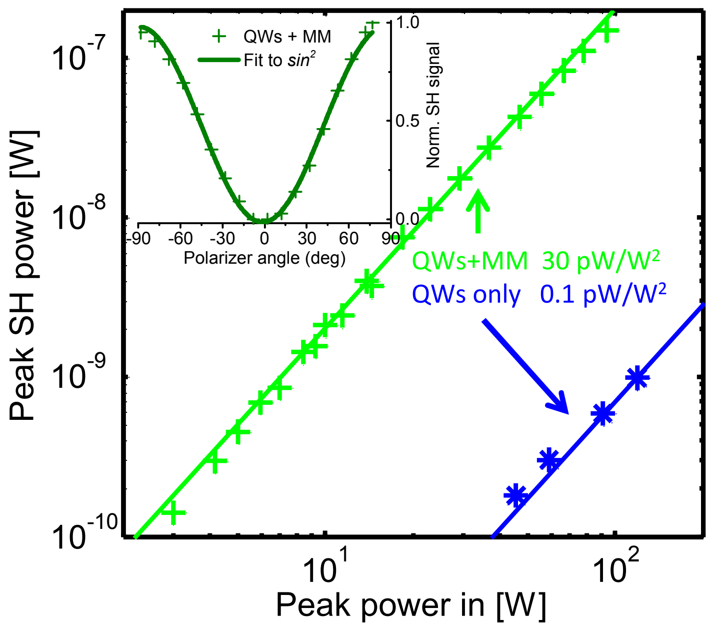
- Design: SHG 3 µm → 1.5 µm (0.4 eV → 0.8 eV)
- Traditional band structure calculation <u>not enough</u>
  - Over estimation of IST



Wolf et al. Appl. Phys. Lett. 107, 151108 (2015)

SHG in III-Nitride Strongly Coupled Structures

- **Actual working wavelength 3.2 µm → 1.6 µm**

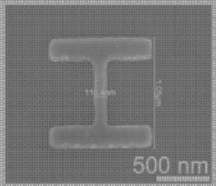


2+ order of magnitude improvement with respect to QWs only

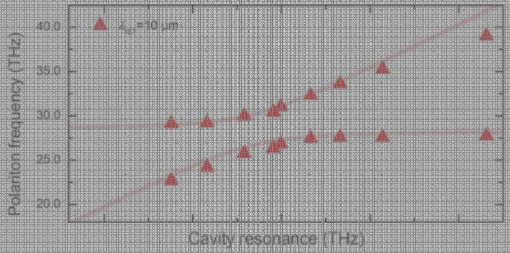
Wolf et al. Appl. Phys. Lett. 107, 151108 (2015)

Outline of the Talk
Strong Light-Matter Interaction

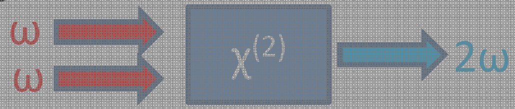
- Show how to use metamaterial nanoresonators to



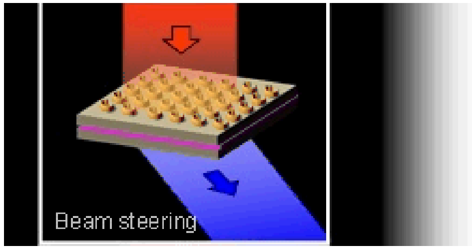
- Achieve strong coupling with intersubband transitions (ISTs) in quantum wells (QWs)



- Achieve efficient second harmonic (SH) generation in ISTs

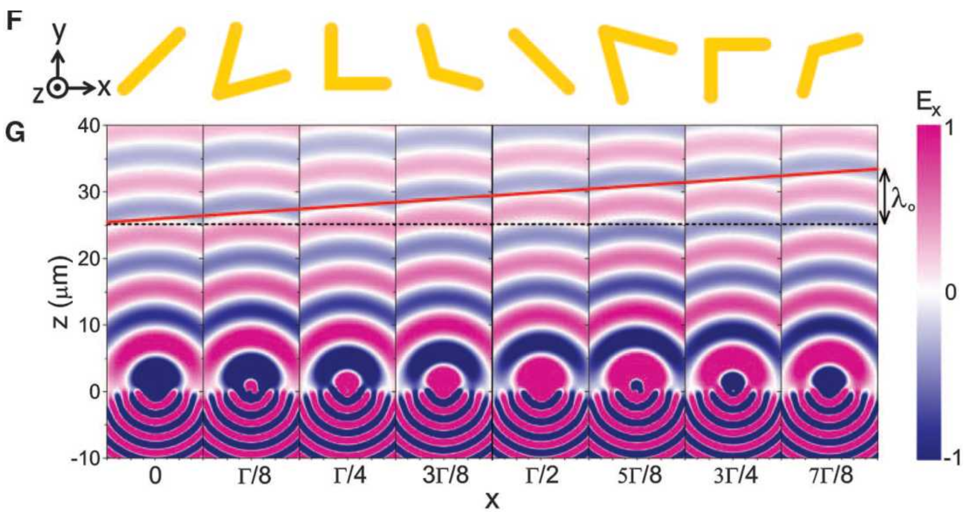


- Form a metasurface for beam manipulation of the SH signal



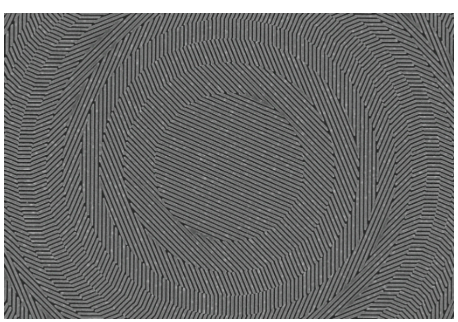
Beam Manipulation with Metasurfaces

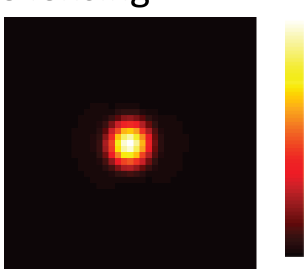
Phase gradient to achieve anomalous refraction



Yu et al. *Science* **334**, 333 (2011)

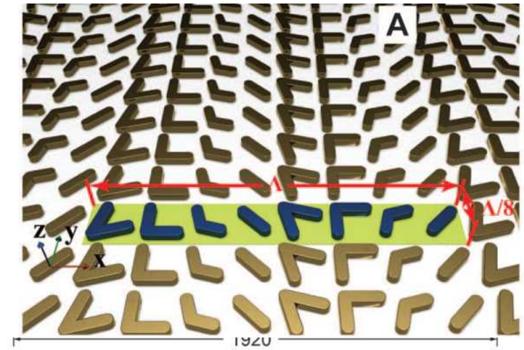
Phase gradient to achieve lensing

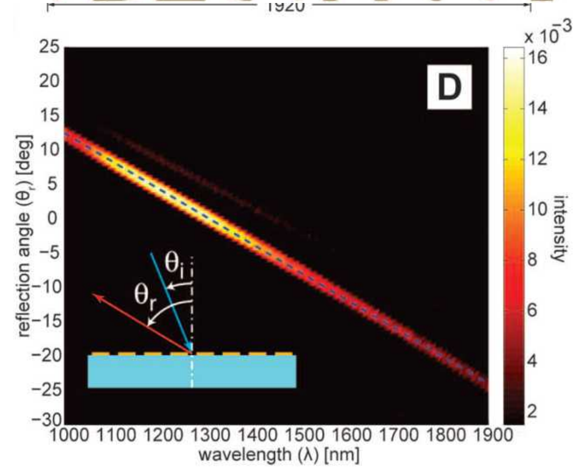




Lin et al. *Science* **345**, 298 (2014)

Phase gradient to achieve anomalous reflection

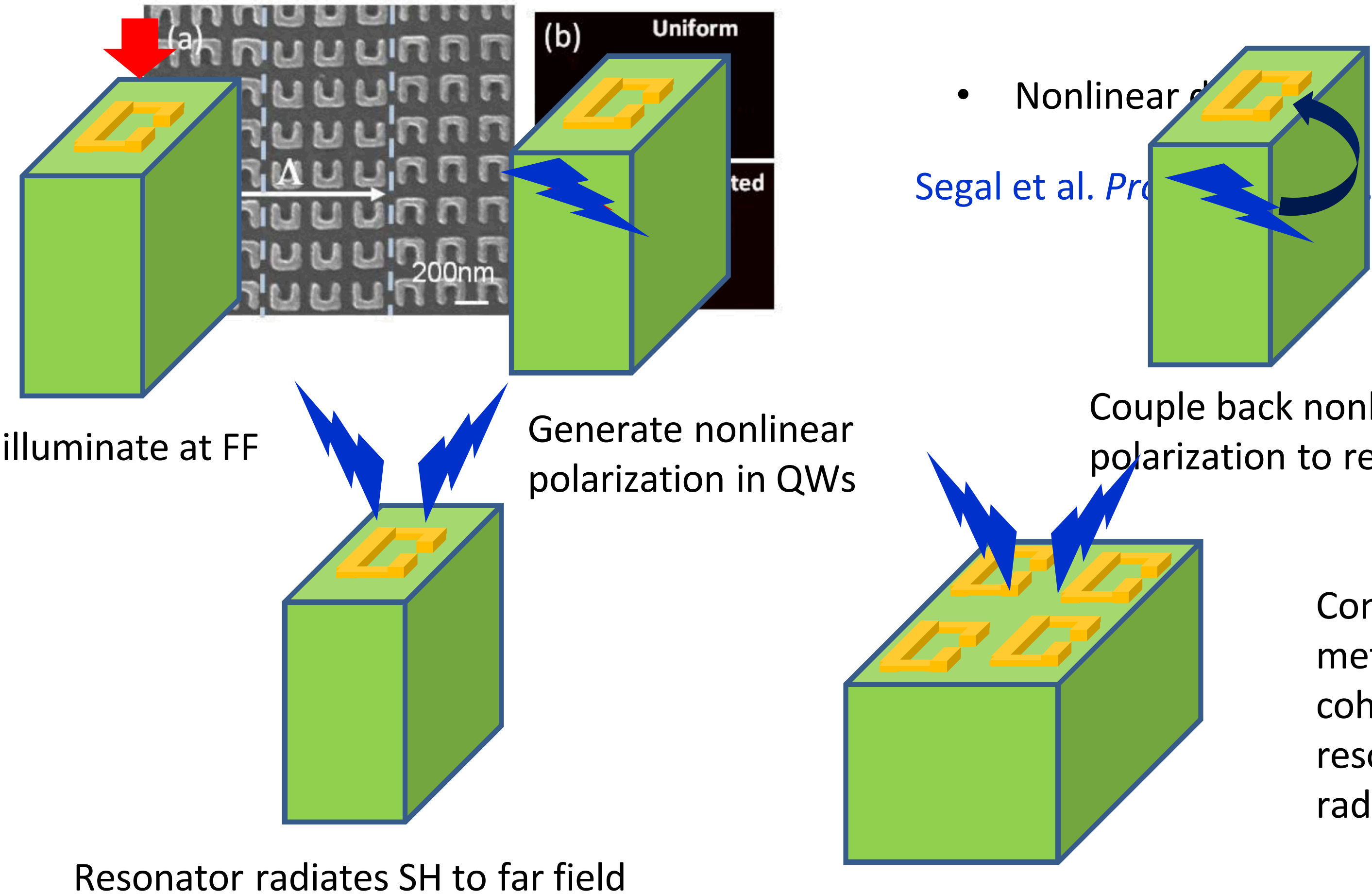




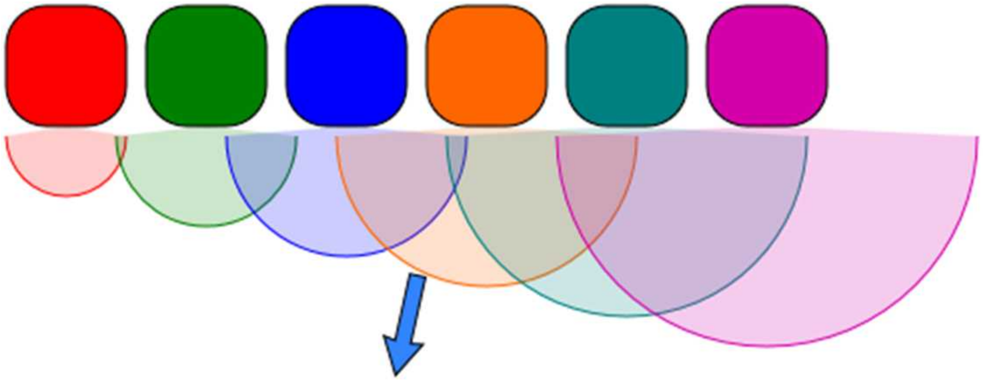
Ni et al. *Science* **335**, 427 (2012)

Beam Manipulation of SH Radiation

- Recent independent work has shown manipulation of SH radiation coming from metallic metasurfaces
- Our approach



Phased Arrays - Schematic



Identical point sources

+

Radiating with controllable phase difference

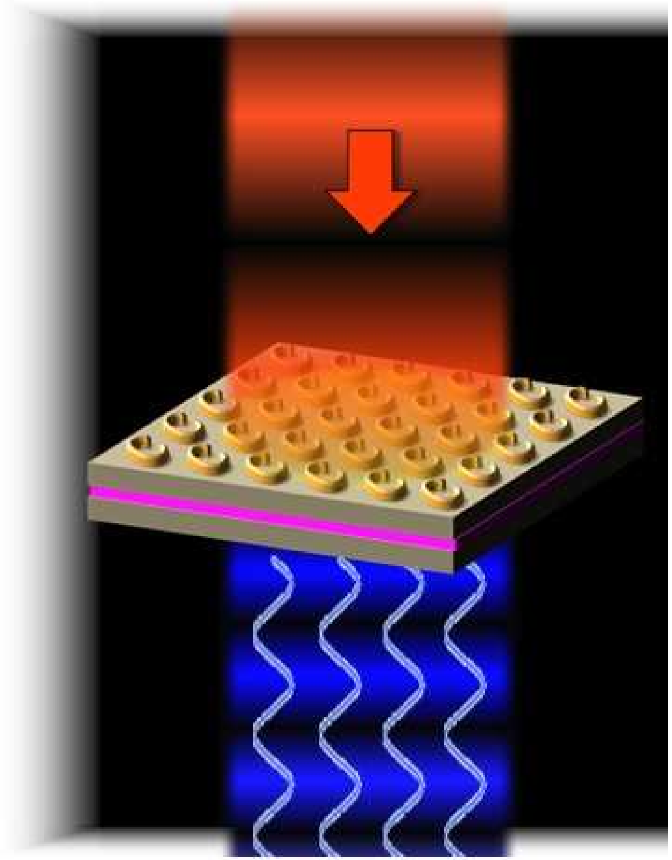
==

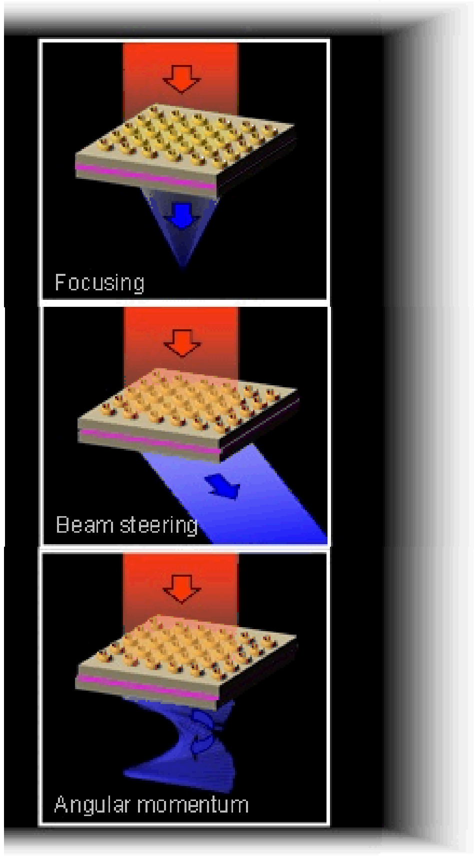
Full control over beam direction and shape

Image from Wikipedia

Array of Second Harmonic Sources

- We created a phase-locked "*feed*" to subwavelength metamaterial resonators which re-radiate a beam with desired spectral, spatial, and polarization properties





So that we can realize

Focusing

Beam steering

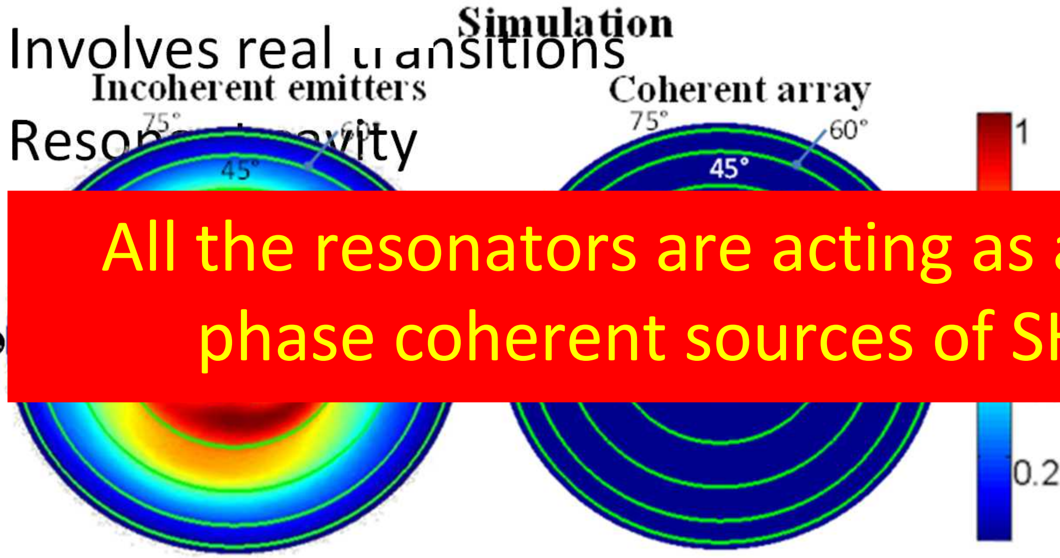
Angular momentum

at the SH frequency

Wolf*, Campione*, et al., Nature Commun. **6**, 7667 (2015)

Spatial Coherence of the Resonators

- Resonant process → $\chi^{(2)}$ has phase
- Involves real transitions
- Resonant cavity



All the resonators are acting as a collection of phase coherent sources of SH radiation

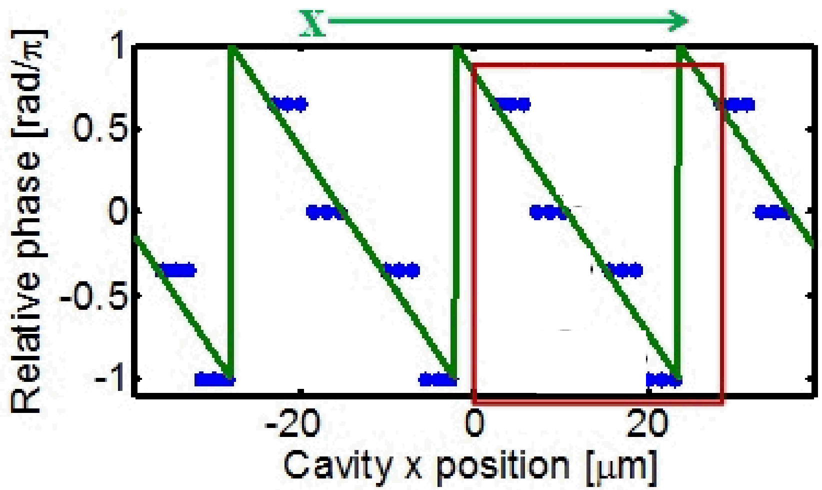
Far-field radiation pattern

O. Wolf et al. *Nature Commun*. 6, 7667 (2015)

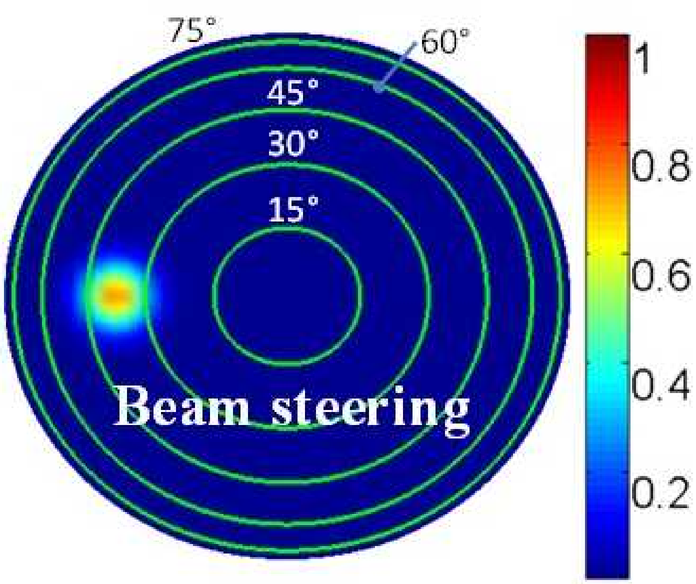
Simulation of SH Beam Steering

- Thus, by slightly varying the resonator shape across the sample, one could create a source with an arbitrary wavefront

Phase variation across the array

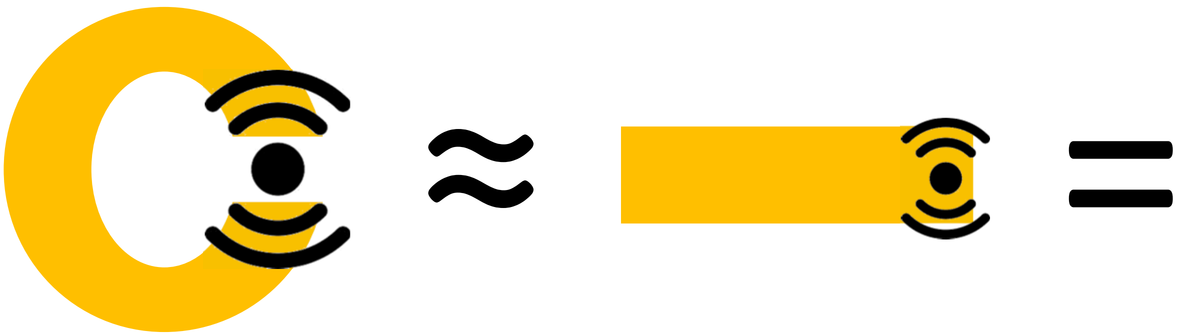


Simulation



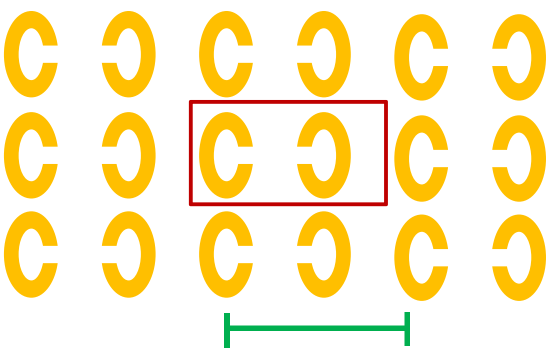
- The angle of the emitted lobe is controlled by the 'phase slope' along the chosen axis and can readily be varied by changing the spacing between phase steps

Beam Manipulation: 2-in-1 device



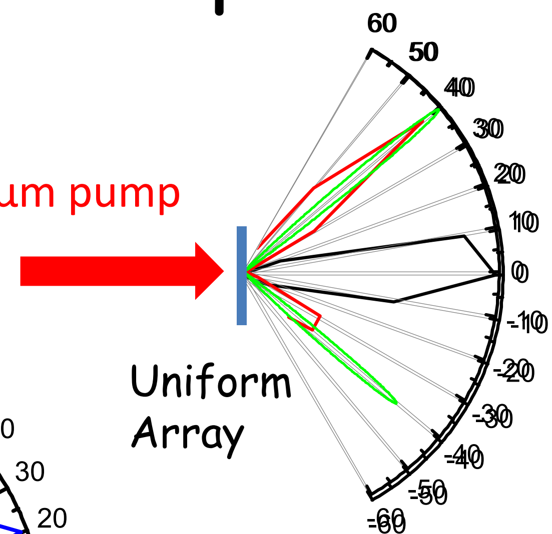
"edge-fed dipole"

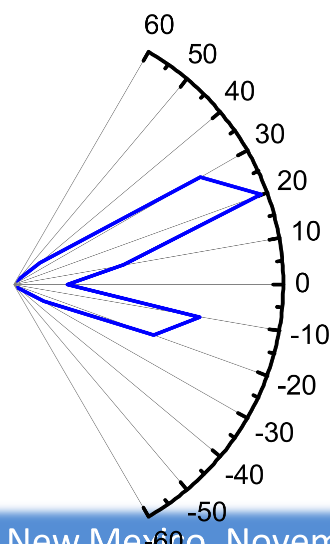
flipping induces π phase shift



Period determines angular separation

O. Wolf et al. *Nature Commun*. 6, 7667 (2015)



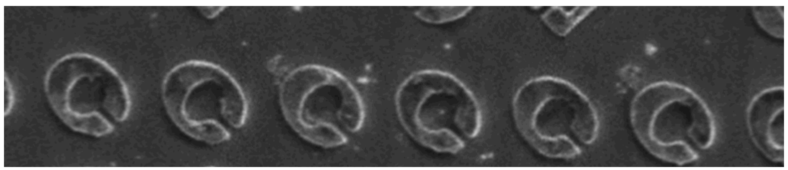


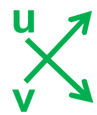
2-in-1:

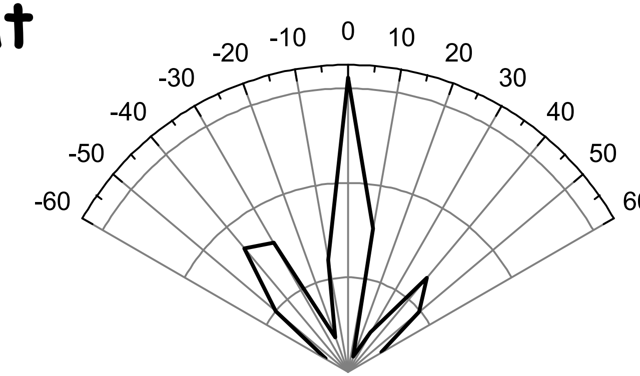
Source +beam splitter

Beam Manipulation: 3-in-1 device

- Cavities radiate polarized light







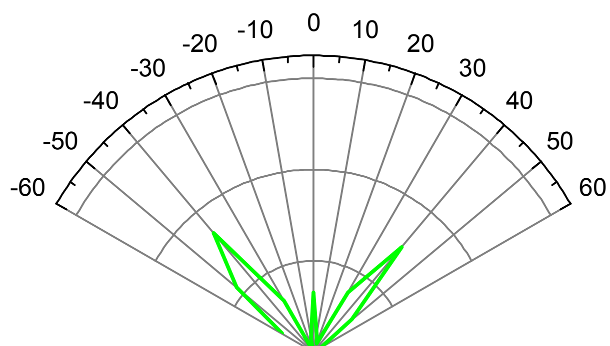
unpolarized

Pump polarization

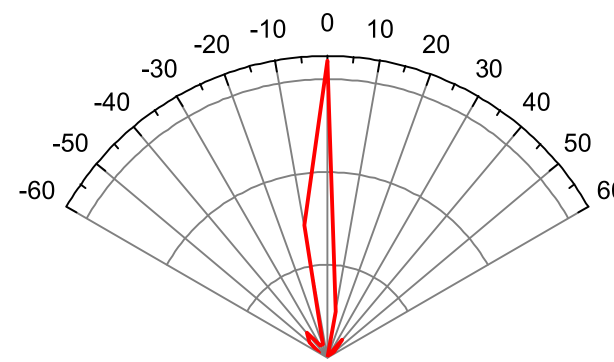
3-in-1:

Source +

Polarizer + Beam Splitter



v polarized



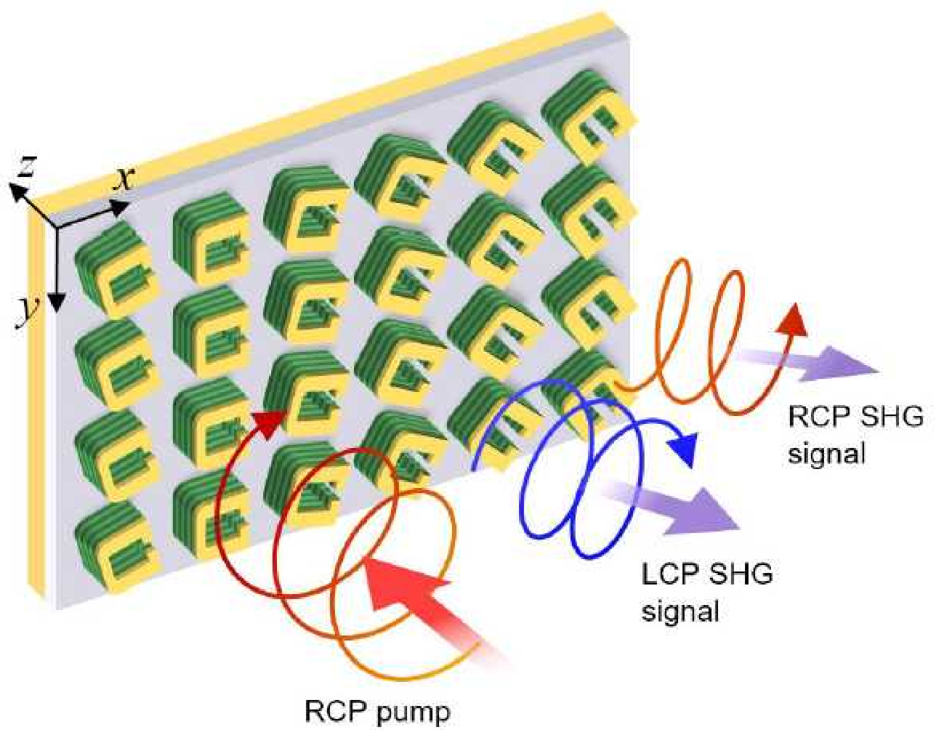
u polarized

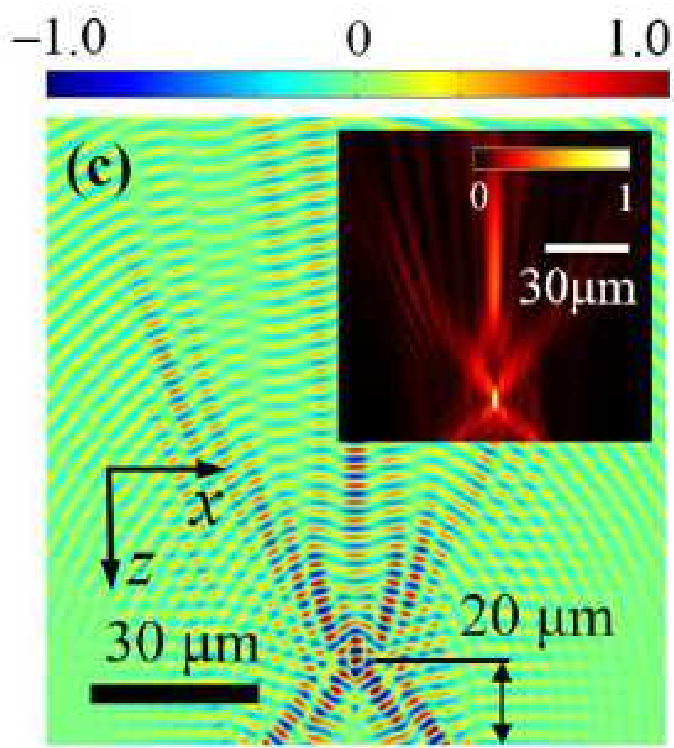
O. Wolf et al. *Nature Commun*. 6, 7667 (2015)

Latest Developments in the Literature

- Very recently, the Pancharatnam-Berry phase approach has been theoretically applied to nonlinear metasurfaces to achieve focused SH beam

Tymchenko et al. *arxiv*:1510.07306 (2015)

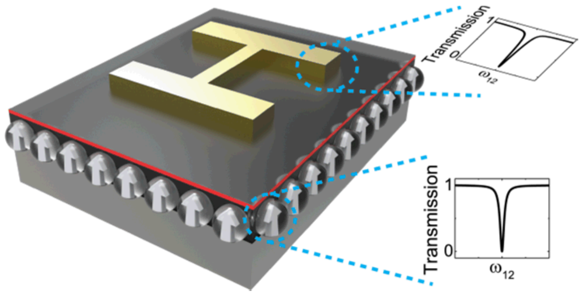


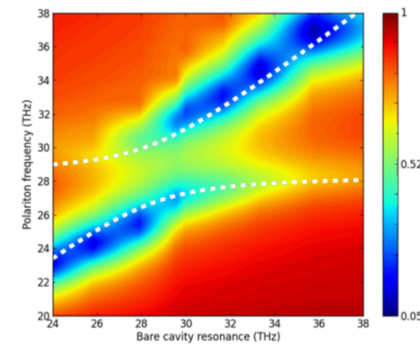


This is just the beginning – The topic of nonlinear metasurfaces has potentially a lot more to offer!

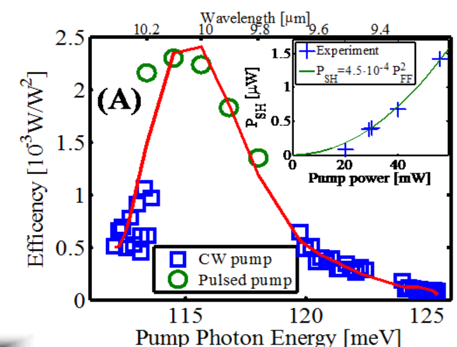
Conclusion

- Metasurfaces are ideally suited for strong light-matter coupling to ISTs in QWs

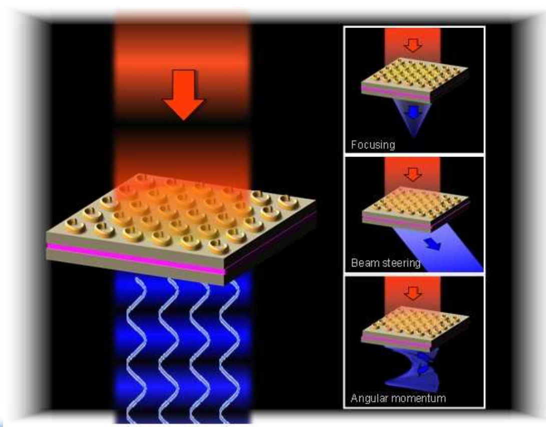


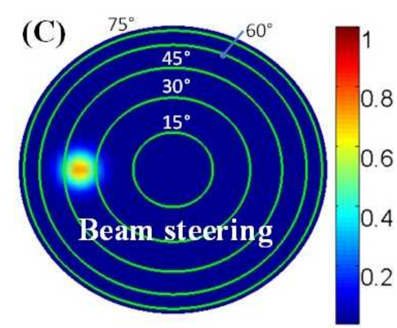


- Promising platform for efficient second harmonic generation with near perfect polarization separation between pump and SH signal



- Manipulation of SH beam for wavefront engineering





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Alex Benz
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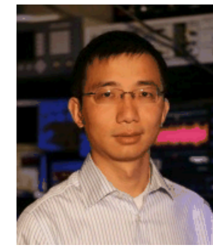

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Lori Basilio
Sandia

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2. **S. Campione** et al. *Phys. Rev. Appl.* 4, 044011 (2015)
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4. A. Benz, **S. Campione**, et al. *Nano Lett.* 15(3), 1959-1966 (2015)
5. A. Benz, **S. Campione**, et al. *ACS Photonics* 1(10), 906-911 (2014)
6. **S. Campione** et al. *Phys. Rev. B* 89, 165133 (2014)
7. **S. Campione** et al. *Appl. Phys. Lett.* 104, 131104 (2014)
8. A. Benz, **S. Campione**, et al. *Opt. Express* 21, 32572-32580 (2013)
9. A. Benz, **S. Campione**, et al. *Nat. Commun.* 4, 2882 (2013)

***These authors contributed equally to this work and are joint first authors**

Thank you for your attention!

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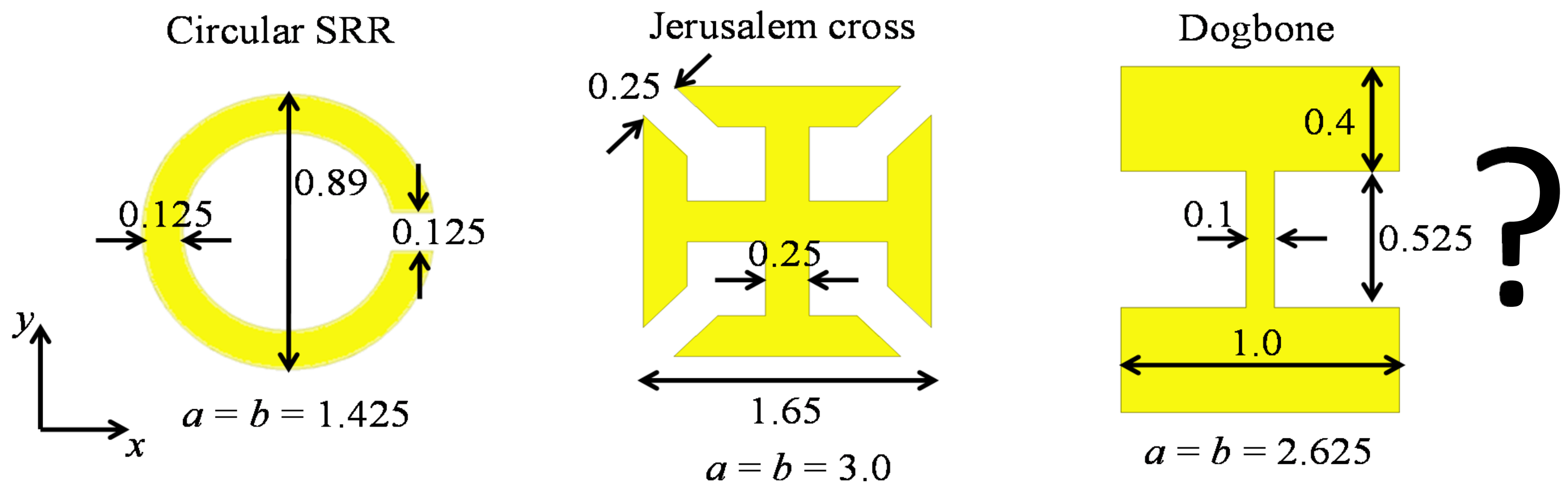
Motivation of circuit modeling
Resonator dependence

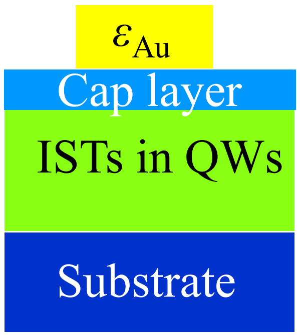
- A circuit interpretation helps understanding
  - the parameters that contribute to strong coupling
  - and how the resonator shapes affect Rabi splitting

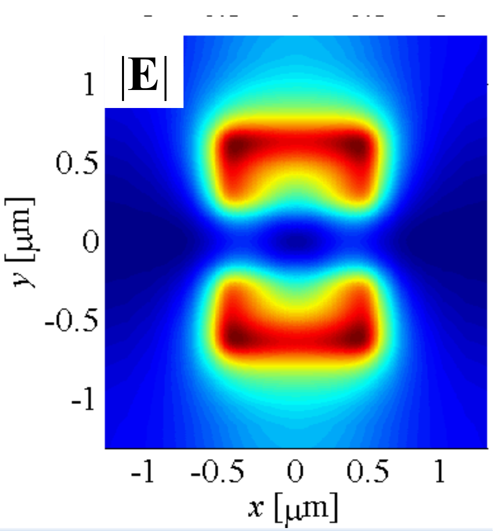


Campione et al., Phys. Rev. B **89**, 165133 (2014)

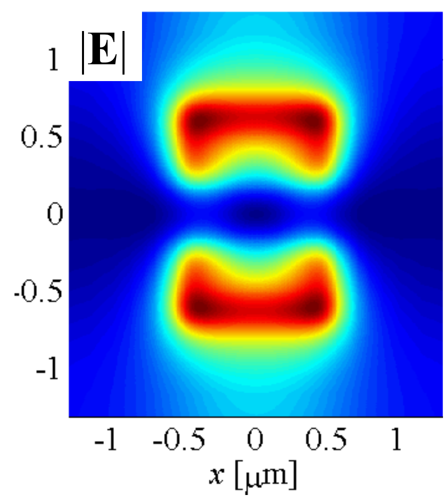
Electrostatic approximation for near fields – Comparison

Dogbone On top of multilayered substrate

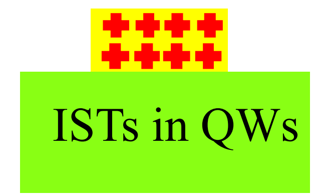


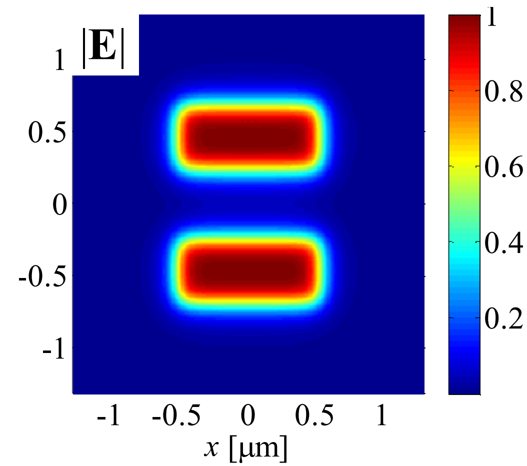


Dogbone On top of anisotropic half space



Distributed set of charges: Electrostatic approximation

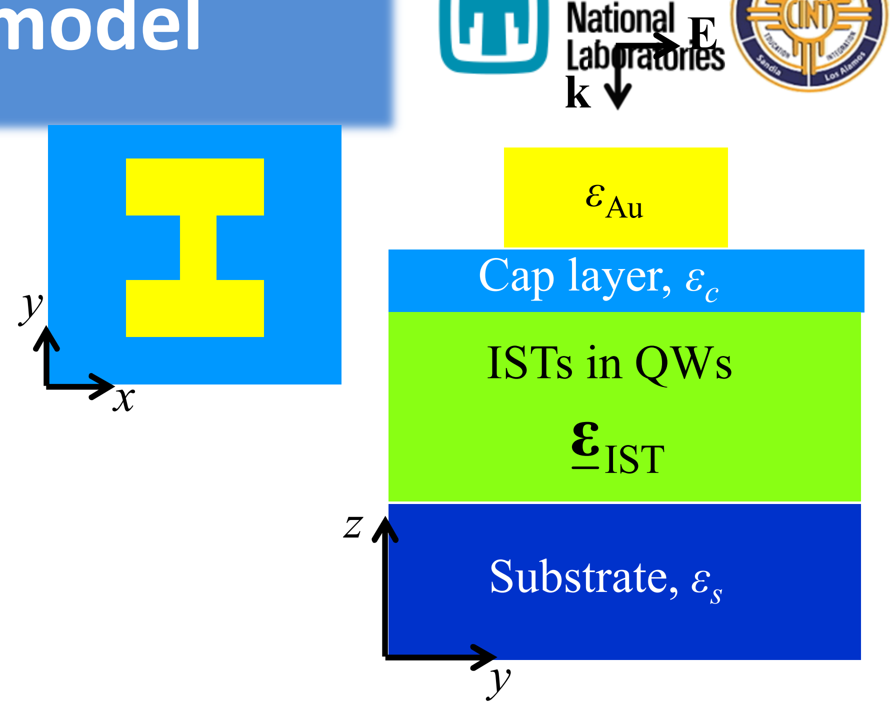


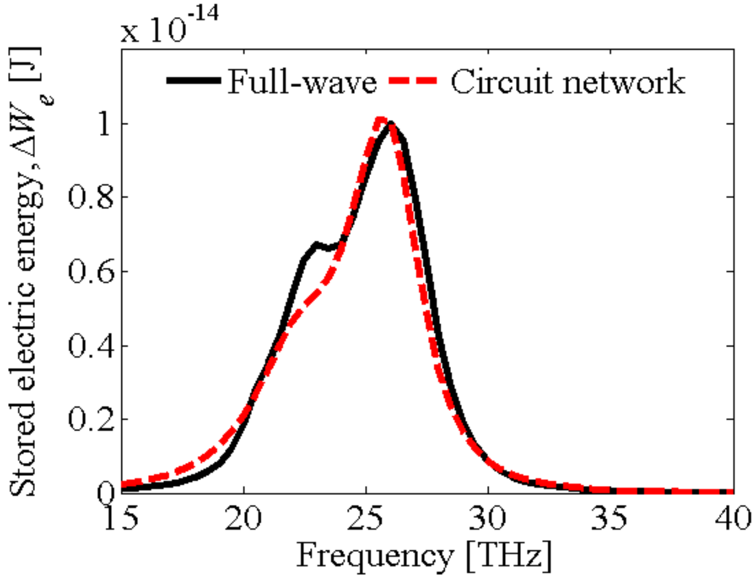


Energy evaluation circuit model

$$\Delta W_e = W_e^{\mathrm{QW}} - W_e^{\mathrm{no\ QW}}$$

The change in energy due to the presence of the QWs is evaluated using both full-wave simulations and circuit network model





The agreement is quite remarkable given the electrostatic approximation used

Energy evaluation circuit model

$$\Delta W_e = W_e^{\text{QW}} - W_e^{\text{no QW}}$$

$$W_e^{\text{QW}} = \frac{1}{4}\varepsilon_0\left(\varepsilon_z' + \frac{2\omega\varepsilon_z''}{2\gamma}\right)\int\limits_{V_{\text{QW}}}\left|E_z^{\text{QW}}\right|^2 dV + \frac{1}{4}\varepsilon_0\varepsilon_t\int\limits_{V_{\text{QW}}}\left|\mathbf{E}_t^{\text{QW}}\right|^2 dV + \sum_i \frac{1}{4}\varepsilon_0\varepsilon_i\int\limits_{V_i}\left|\mathbf{E}^{\text{QW}}\right|^2 dV$$

$$W_e^{\text{no QW}} = \sum_j \frac{1}{4}\varepsilon_0\varepsilon_j\int\limits_{V_j}\left|\mathbf{E}^{\text{no QW}}\right|^2 dV$$

$$W_e^{\text{QW}} = \frac{1}{4}\left(C' + \frac{2\omega C''}{2\gamma}\right)\left|V_C^{\text{QW}}\right|^2$$

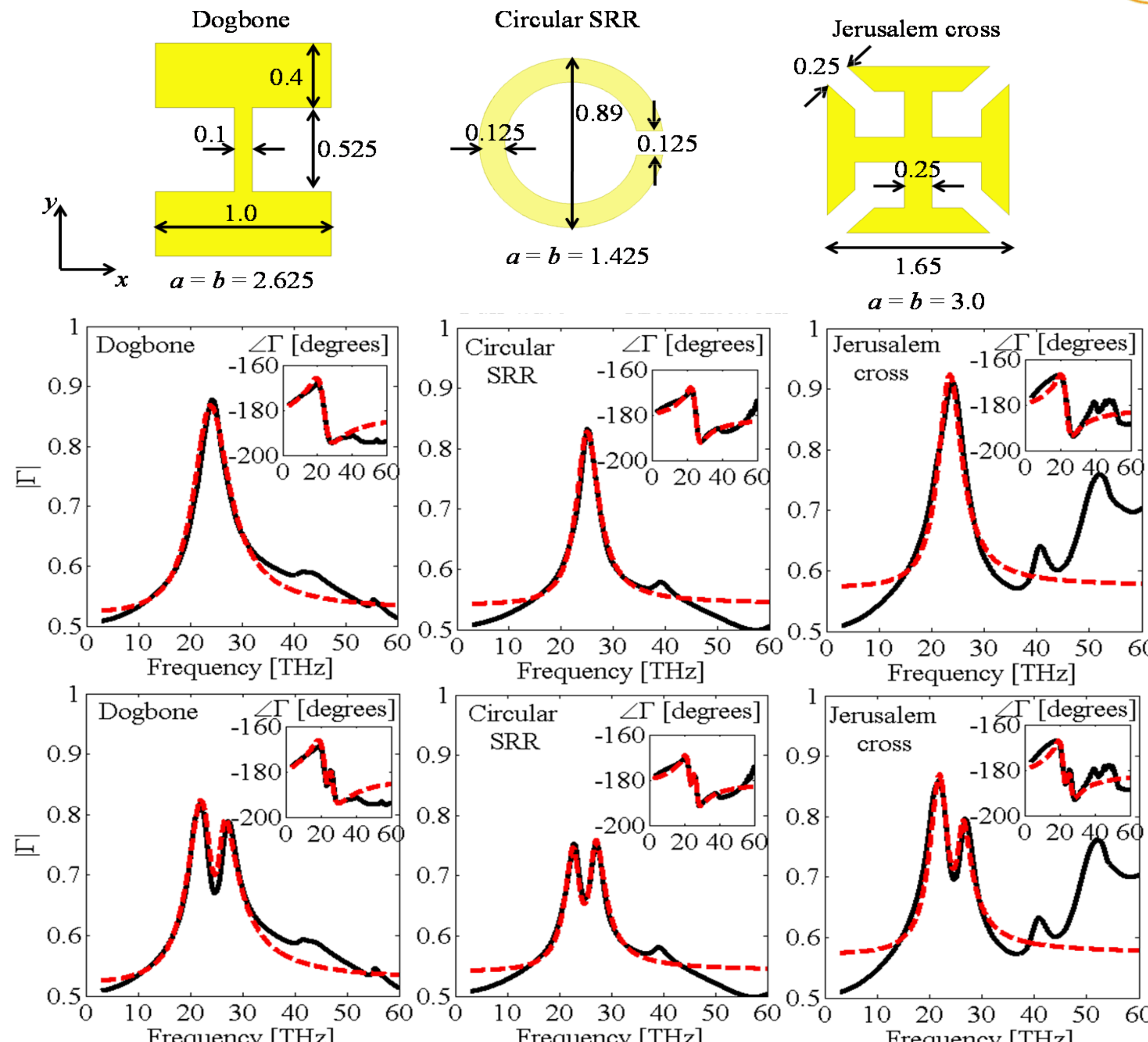
$$W_e^{\text{no QW}} = \frac{1}{4}C_{\text{ms}}\left|V_C^{\text{no QW}}\right|^2$$

Spectra various resonators circuit model

- The agreement is better observed by plotting the reflection for a specific scaling factor

WITHOUT QUANTUM WELLS

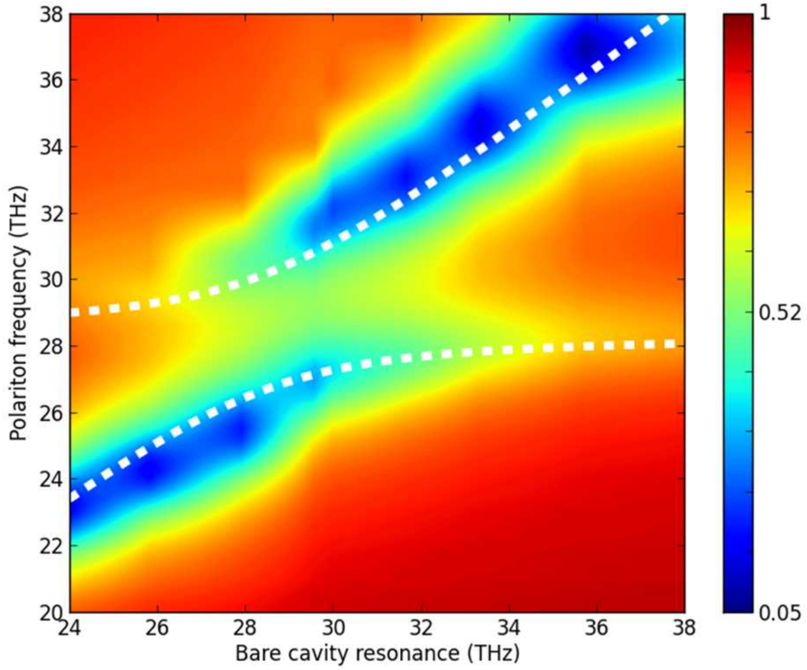
WITH QUANTUM WELLS



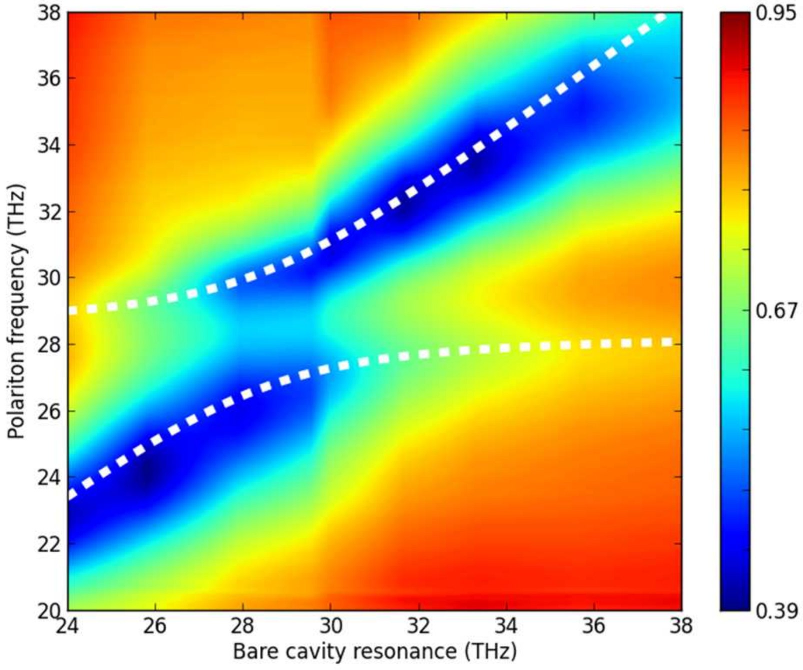
experimental results

- We thus plot the transmission maps as a function of polariton and bare cavity frequencies from full-wave simulations and FTIR measurements at room temperature

Full-wave



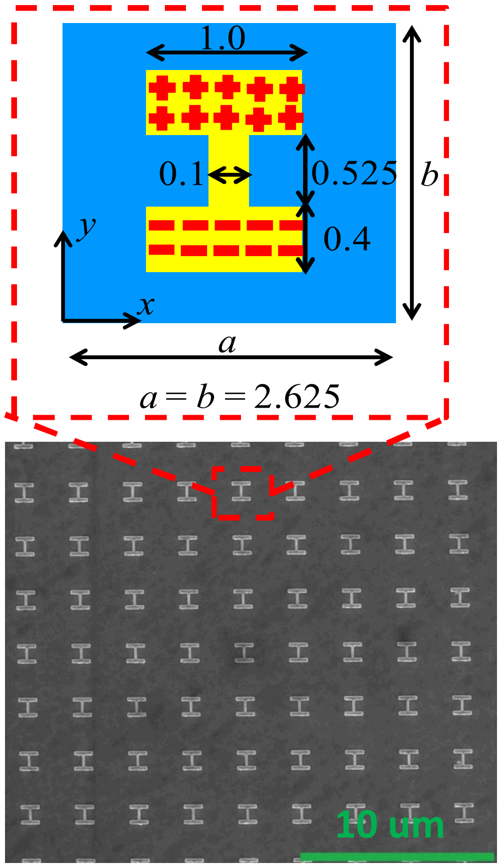
Experiment



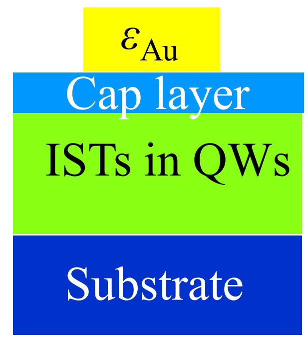
- Note the good agreement of the two results

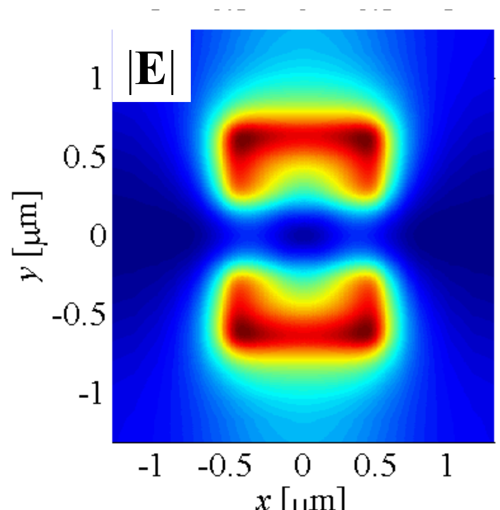
Electrostatic approximation for near fields

Set of distributed charges below the dogbone paddles

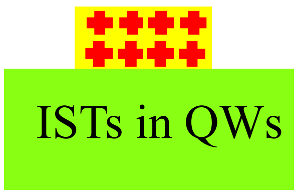


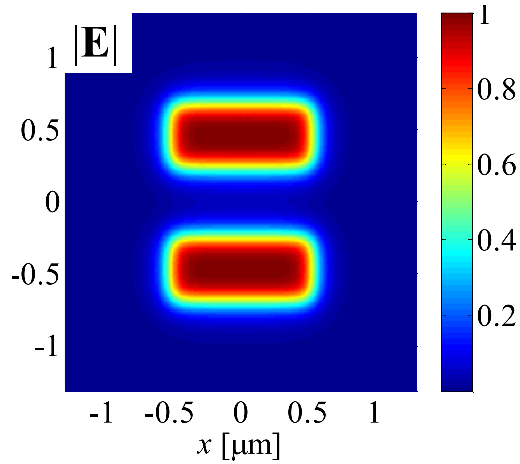
Dogbone on top of multilayered substrate



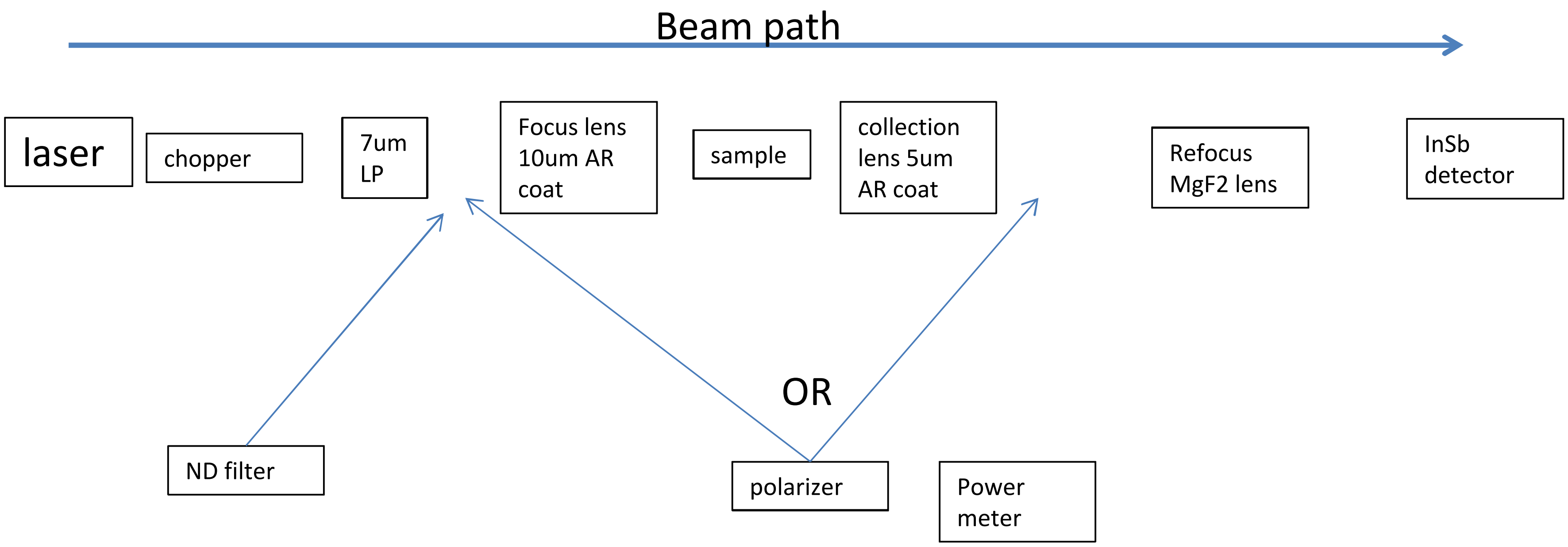


Distributed set of charges: Electrostatic approximation

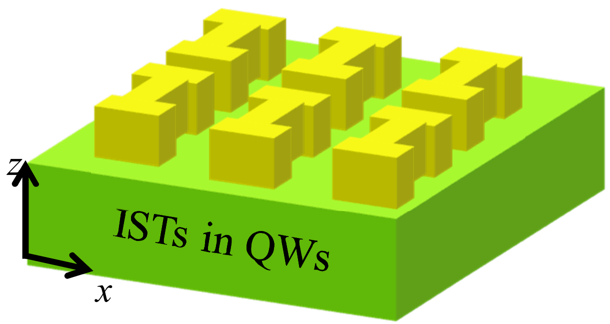




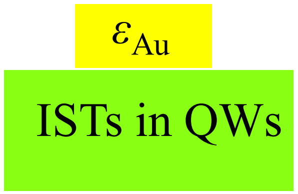
SHG- setup

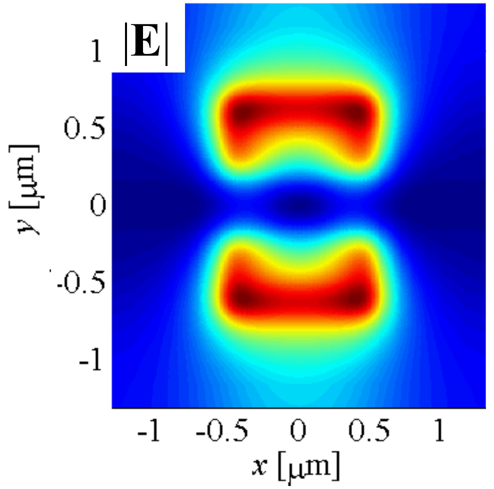

Beam path
laser
chopper
7um LP
Focus lens 10um AR coat
sample
collection lens 5um AR coat
Refocus MgF2 lens
InSb detector
ND filter
OR
polarizer
Power meter

Electrostatic approximation for near fields – Comparison

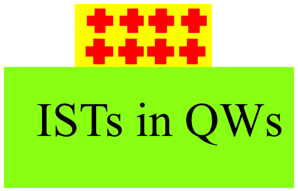


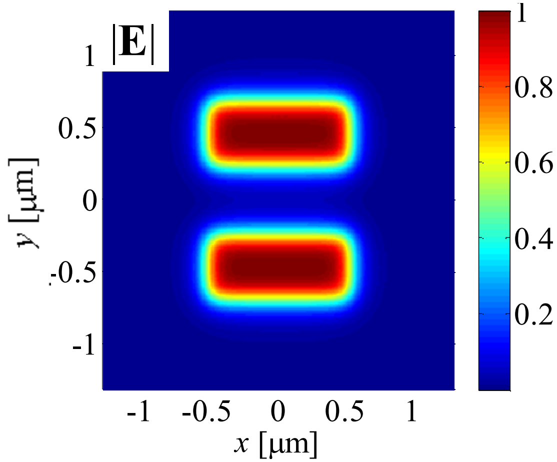
Resonator On top of anisotropic half space





Distributed set of charges: Electrostatic approximation

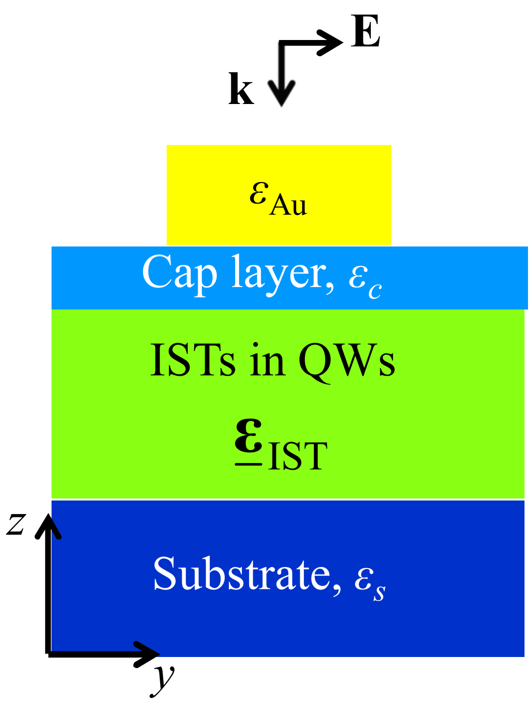




Time and spectral measurements

- The normal plane wave illumination induces the resonating metasurface to generate near fields that contain substantial z polarized electric fields

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



- These near fields excite electrons in the optical transition of the QWs, energy is exchanged between the two systems, inducing a splitting in the spectral properties (e.g., transmission): 3.5 THz splitting

- When looking in time domain, the presence of a Rabi oscillation is also sought to confirm strong coupling regime: 33 fs oscillation, 480 fs beating