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Metasurfaces strongly coupled to intersubband transitions: Circuit model and second order nonlinear processes

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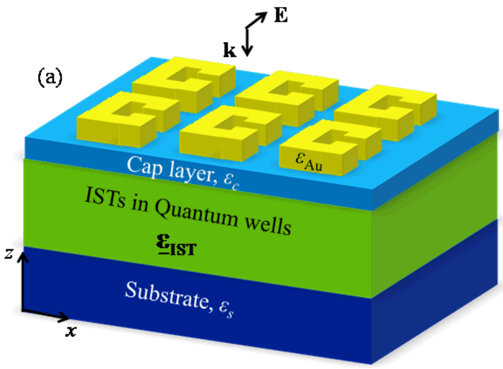
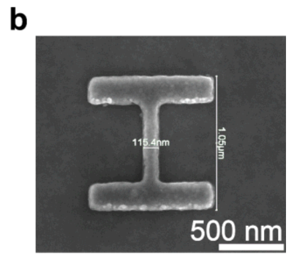
Outline of the talk





Strong coupling between a metasurface and intersubband transitions (ISTs) in quantum wells (QWs)

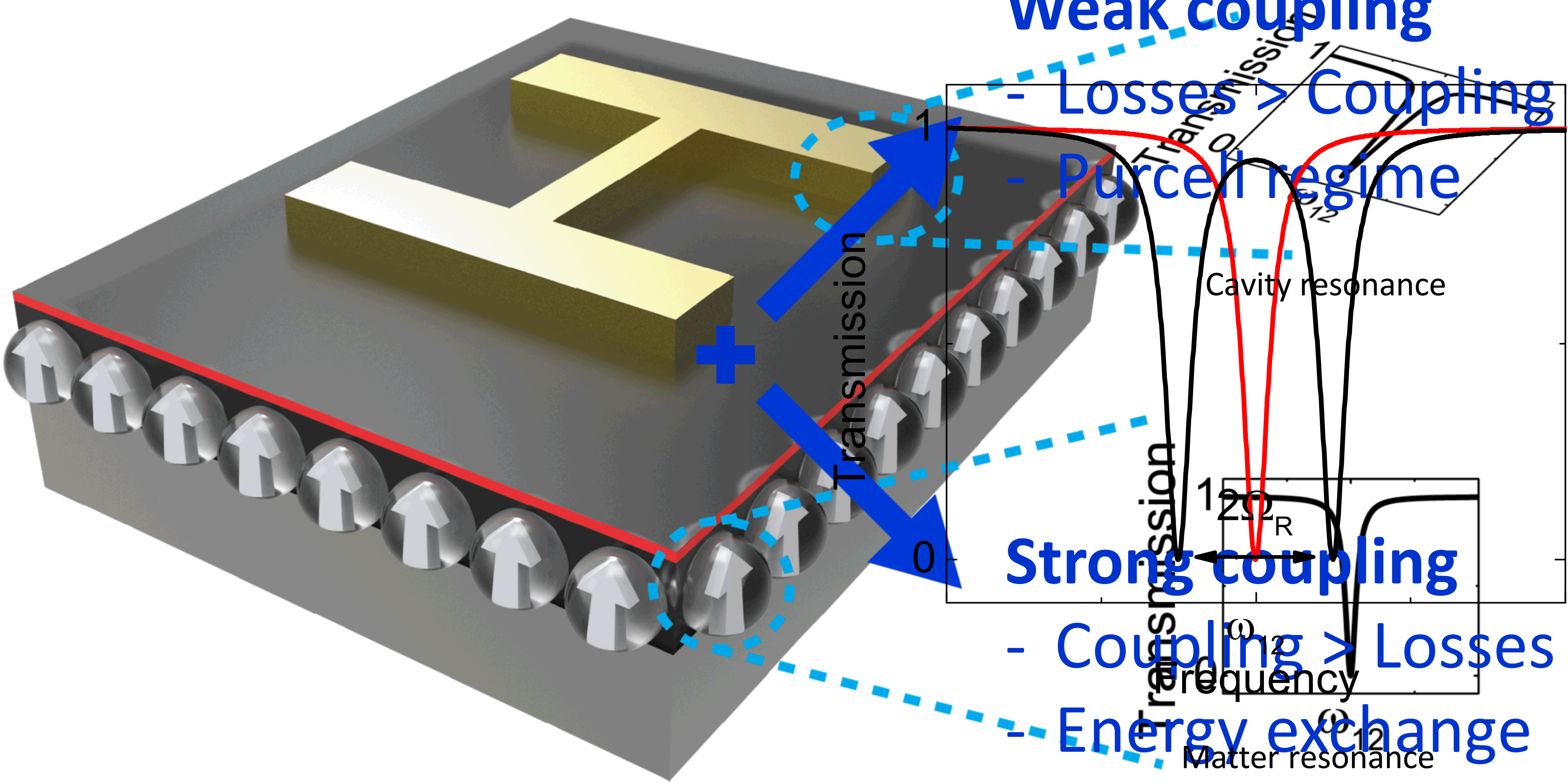
Metasurface = array of resonators

- Introduce strong coupling between a metasurface and ISTs in QWs
- Introduce an electrodynamic model of strong coupling
  - Derive and validate a circuit model
- Get a phenomenological explanation of strong coupling
  - Helpful for further extension beyond strong coupling regime
- Applicability of such platform for efficient second harmonic generation

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

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

Light-matter coupling in metasurfaces coupled to ISTs in QWs



Weak coupling

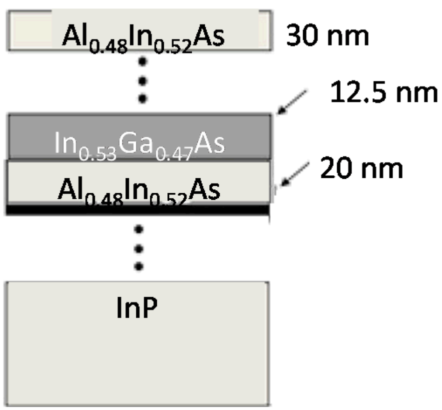
- Losses > Coupling
- Purcell regime

Strong coupling

- Coupling > Losses
- Energy exchange
- Rabi frequency

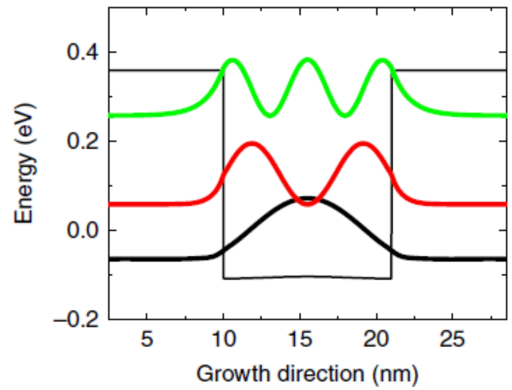
Benz et al., Nat. Commun. **4**, 2882 (2013)

Matter resonance: ISTs in QWs



InGaAs homogeneously doped

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



Optically active transition: between ground state

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

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

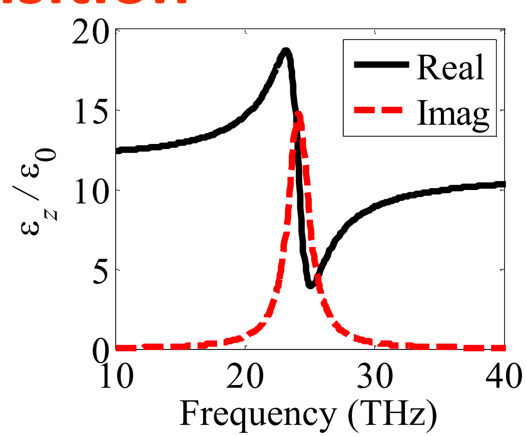
Only z polarized light can interact with the QWs and excite the optically active transition

- The … pic materia…

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

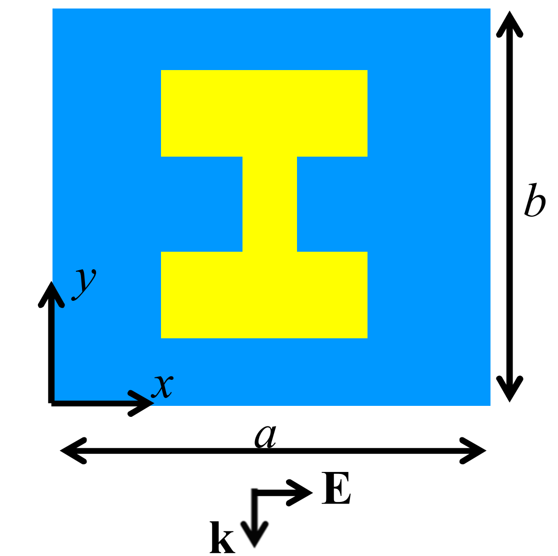
$$\varepsilon_z = \varepsilon_b + \chi \qquad \varepsilon_b = 11\varepsilon_0$$

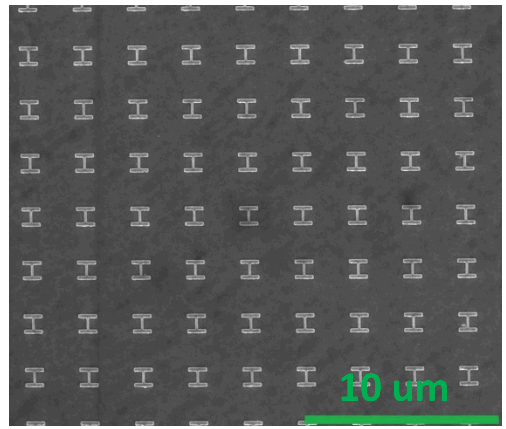
$$\chi = \frac{Ne^2}{m^*} f \frac{1}{\omega_0^2 - \omega^2 - 2i\gamma\omega}$$

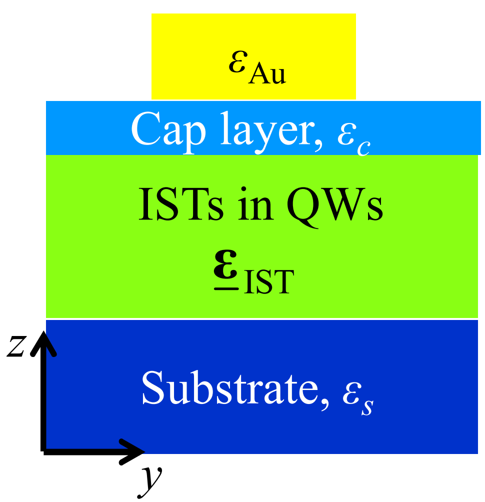


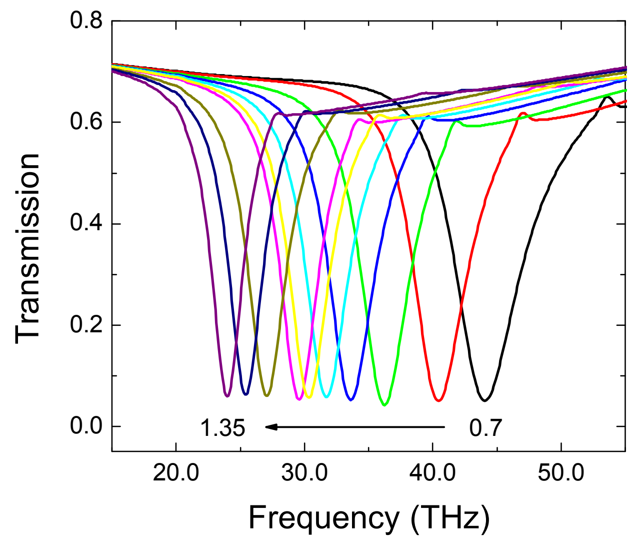
Cavity resonance: Metasurface

- Under normal plane wave illumination, the ISTs properties would be inaccessible









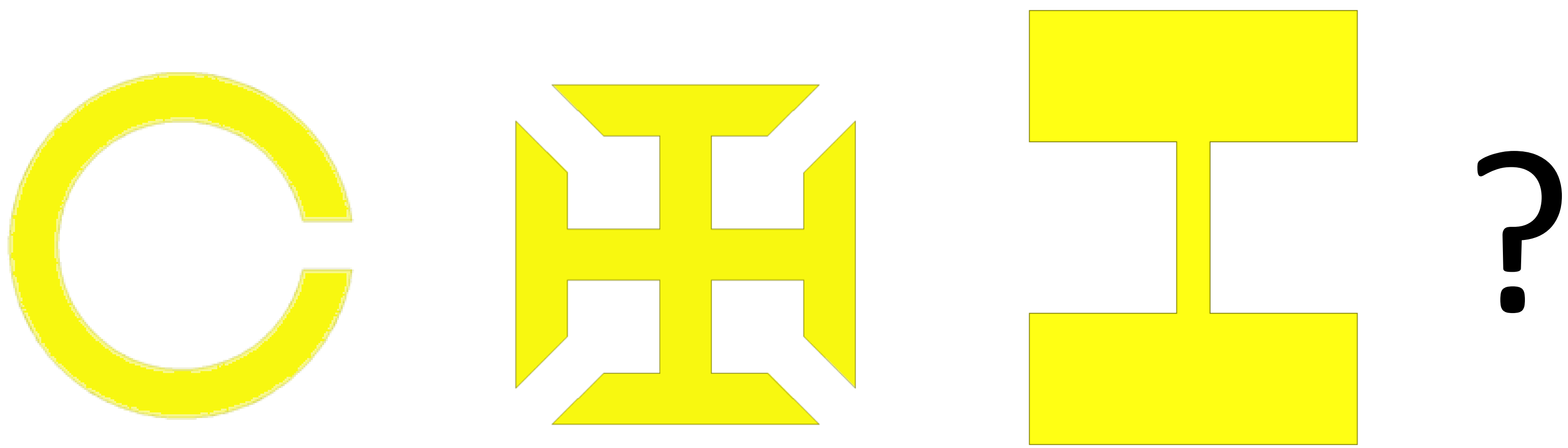
We thus pattern a metasurface of metallic resonators for two reasons:

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

2) Produce strong near fields in order to excite the QWs and promote electrons in subbands

Motivation of circuit modeling
Resonator dependence

- Different resonator geometries may lead to different Rabi splittings
- A circuit interpretation helps understanding
  - the parameters that contribute to strong coupling
  - and how the resonator shapes affect Rabi splitting

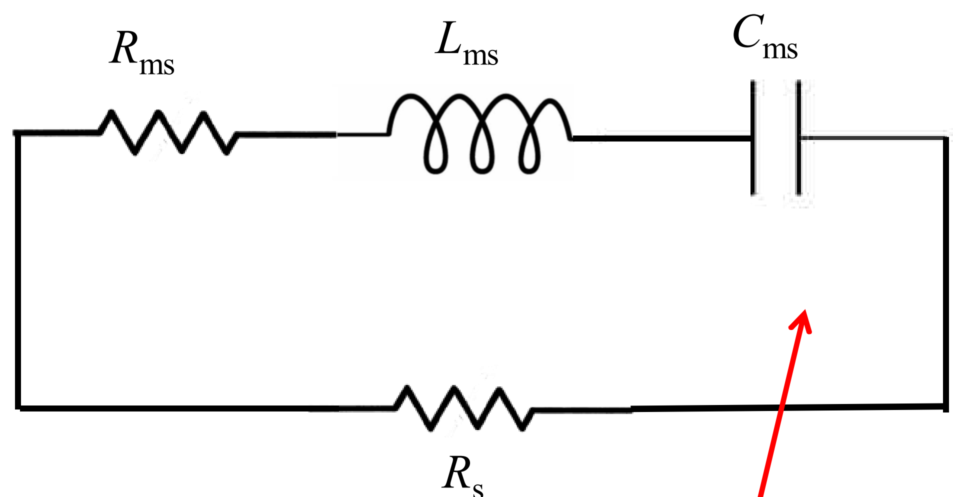


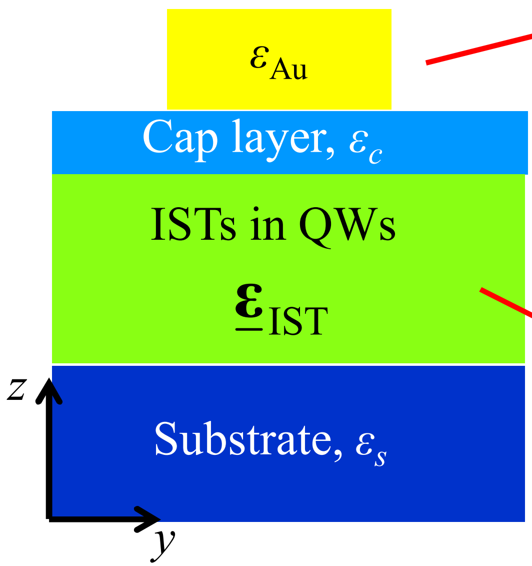
Circular SRR   Jerusalem cross   Dogbone

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

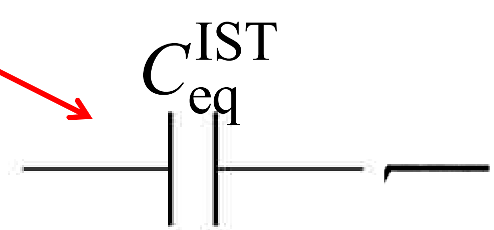
Modeling: introduction of a circuit model

- 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

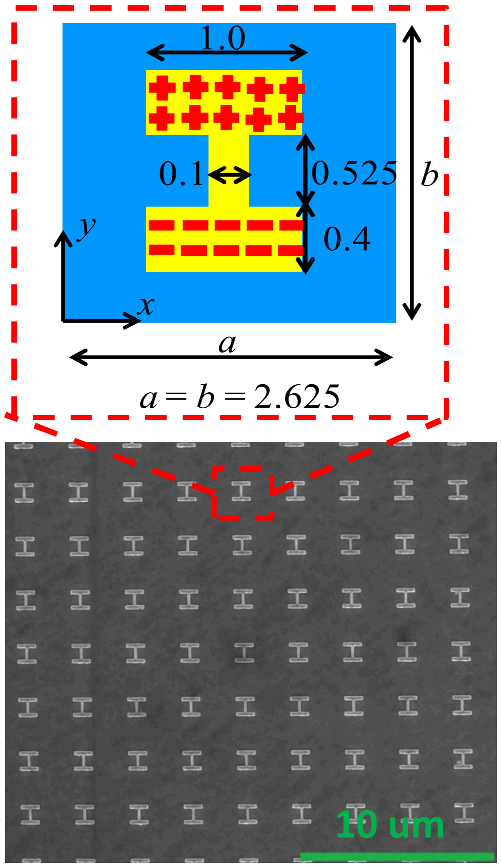


?

- Strong coupling should appear as a capacitor
- The plane wave in the substrate can be modeled through a resistive load
- But how shall it be connected?

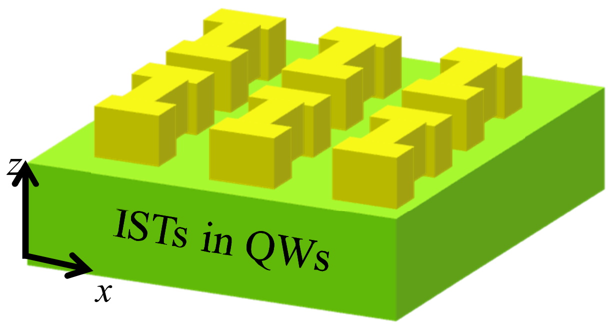
Electrostatic approximation for near fields – IST dipole rule

Consider a set of distributed charges below the dogbone paddles

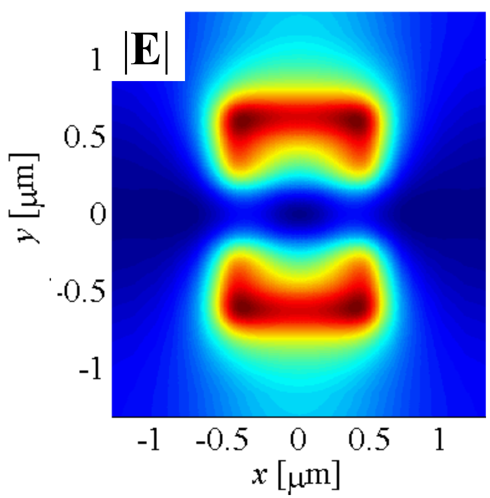


- The ISTs selection rule requires z polarized electric fields
- z polarized electric fields are confined in the near fields of the resonators
- Near fields can be described resorting to the electrostatic approximation

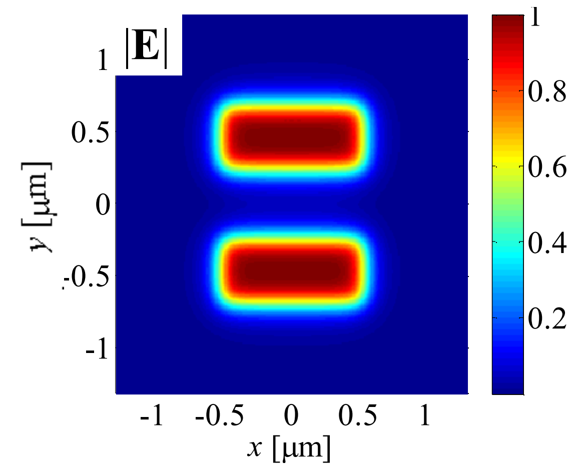
Electrostatic approximation for near fields – Comparison



Resonator On top of anisotropic half space

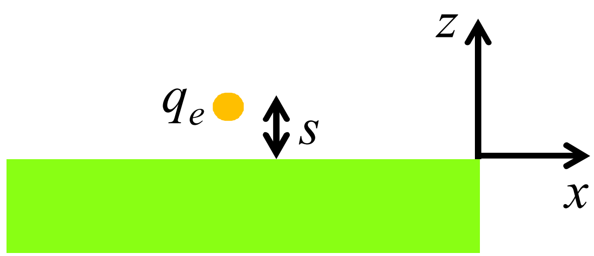


Distributed set of charges: Electrostatic approximation



Capacitor from a point dipole over an anisotropic half space

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



- We can estimate the electric potential of a charge

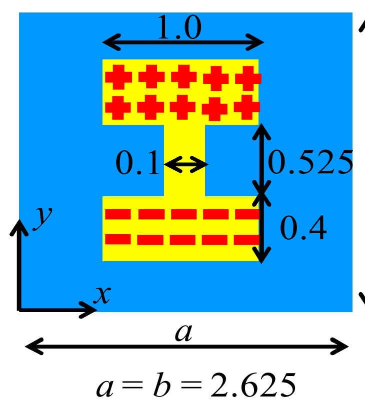
$$\phi_e = \phi_e(\varepsilon_t, \varepsilon_z)$$

This capacitor is a measure of the near-field interaction between dipole and matter (anisotropic space)

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

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

ξ: coupling coefficient



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

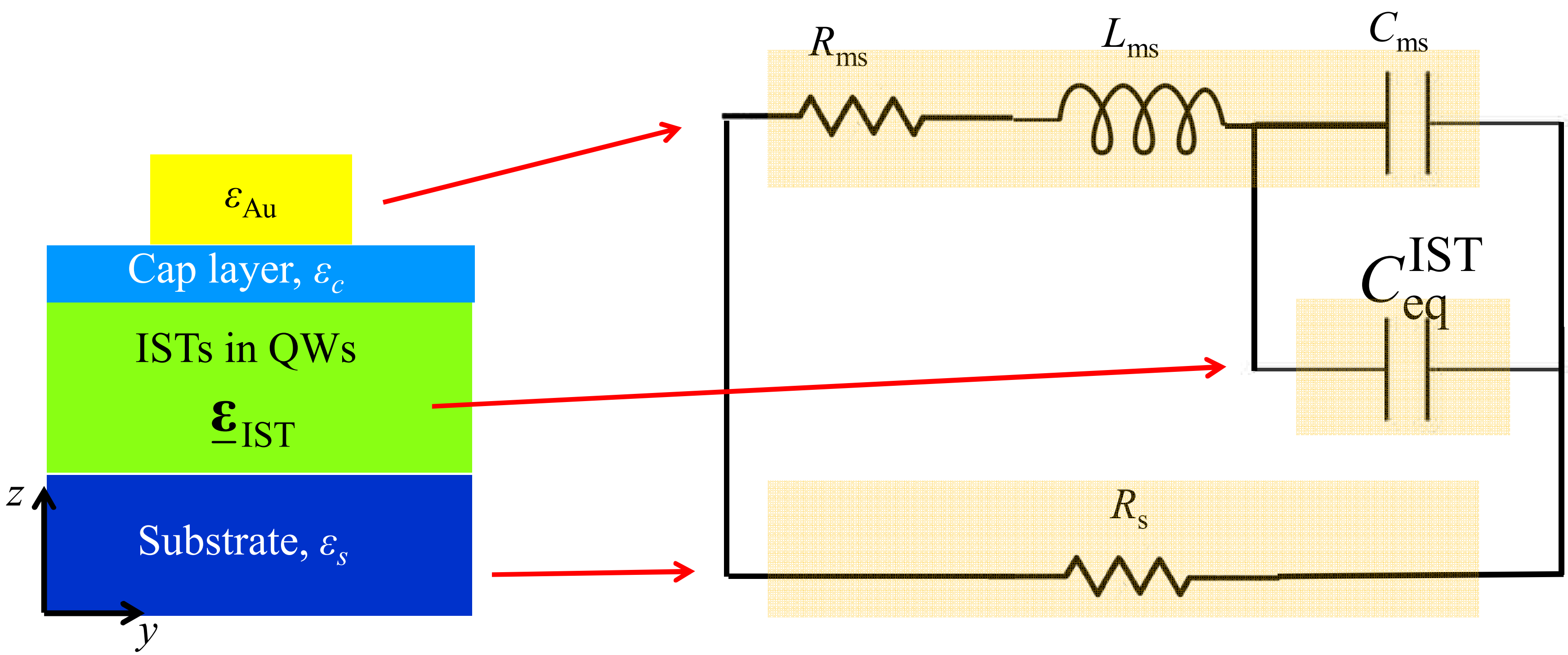
Strong coupling capacitor in place in the circuit model

- The total capacitor is thus the sum of two contributions

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

- The IST capacitor is due to QWs
- Computed and obtained using full-wave and circuit simulations

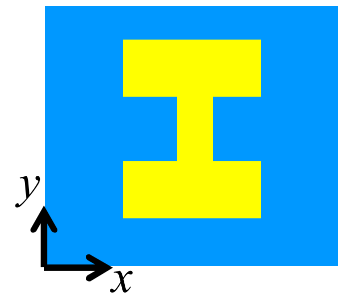
$$C_{\text{eq}}^{\text{IST}} = C_{\text{ms}} \left(\sqrt{\varepsilon_t \varepsilon_z} - \varepsilon_t \right) / \left(\varepsilon_t + 1 \right)$$

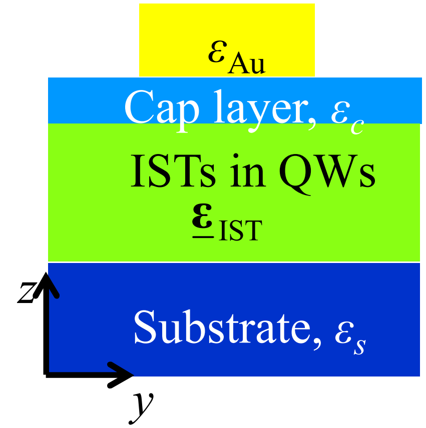


Validation of the circuit model: Spectral properties

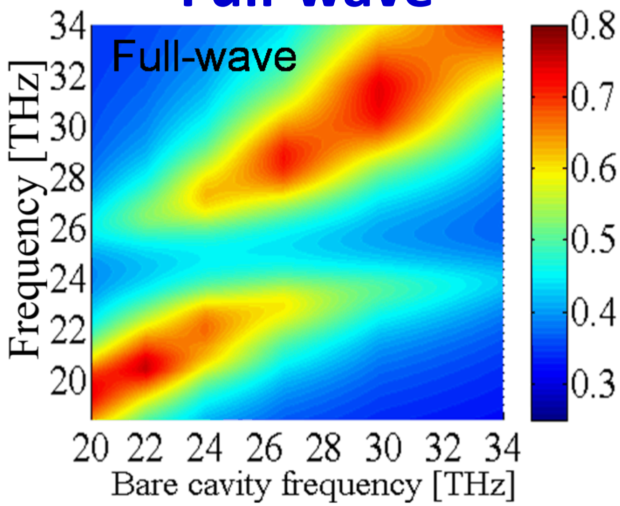
Campione et al., Phys. Rev. B **89**, 165133 (2014)

Reflectivity $|\Gamma|^2$

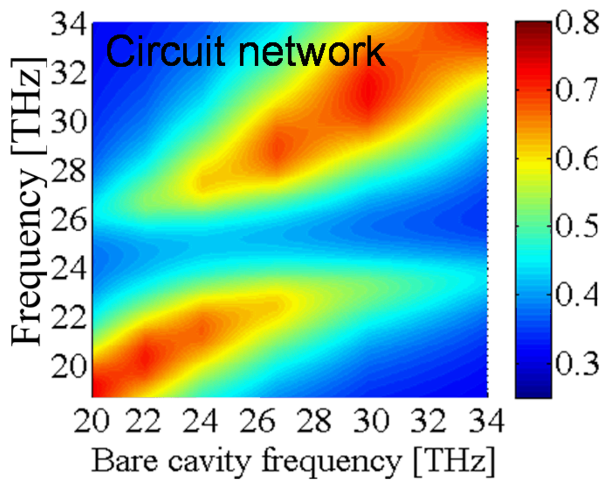




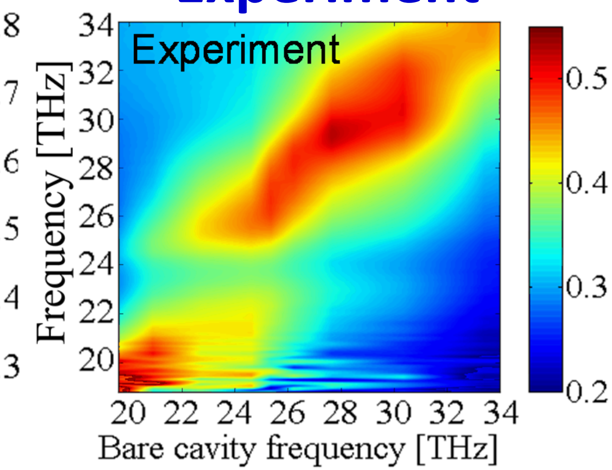
Full-wave



Circuit network



Experiment

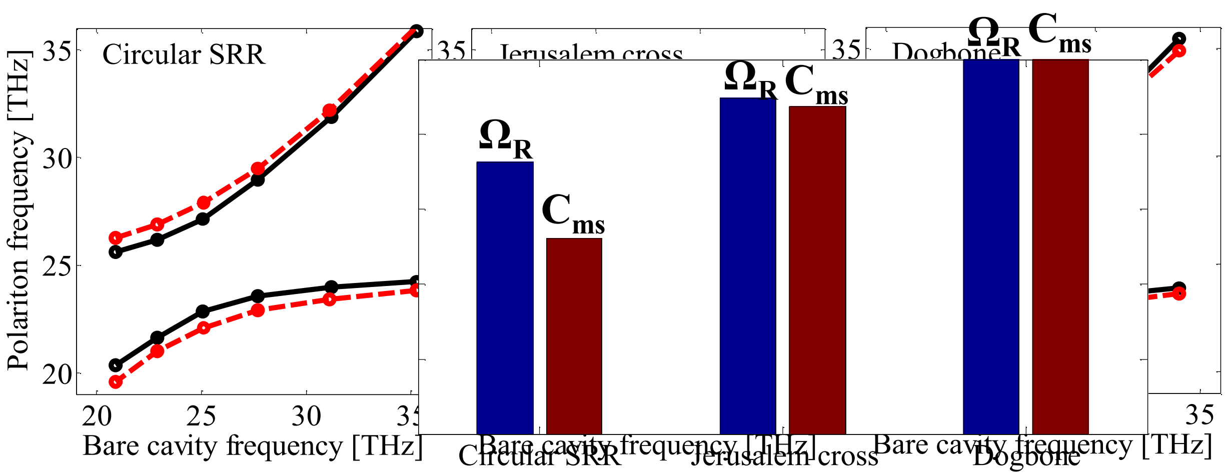


Not only do we recover the resonance frequency locations, but we are also able to quantify the magnitude of reflectivity

Circuit model: how to maximize Rabi splitting – Polariton splitting

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

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



Red dashed: Full-wave

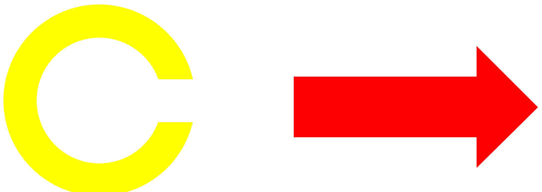
Black solid: Circuit model

- Such narrow splitting is associated to a smaller value of the capacitance C_{ms}
- Note the good agreement with full-wave simulations
- Note the narrower splitting for SRR resonator

$$C = \frac{\sqrt{\varepsilon_t \varepsilon_z} + 1}{\varepsilon_t + 1} C_{ms}$$

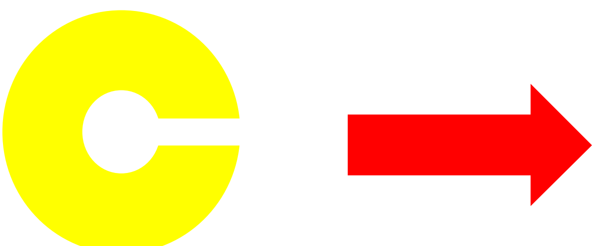
Another example:
Split ring resonators

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



$$C_{ms} = 8.7 \text{ aF}$$
$$\Omega_R = 2.1 \text{ THz}$$

- To increase its capacitance, we increase the metal traces



$$C_{ms} = 13.7 \text{ aF}$$
$$\Omega_R = 2.4 \text{ THz}$$

A larger capacitance corresponds to a larger Rabi frequency

- Dependence with resonator physical dimensions:

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

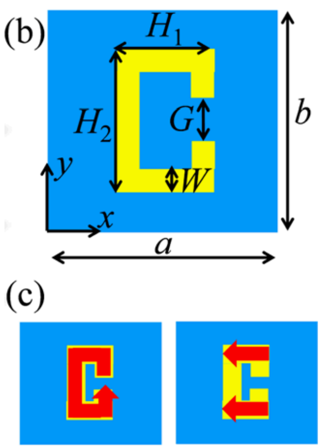
$$C_{gap} = \varepsilon_0 hw/g + \varepsilon_0 \left(h + w + g\right)$$

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

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

Second harmonic generation – Design of the strong coupling structure

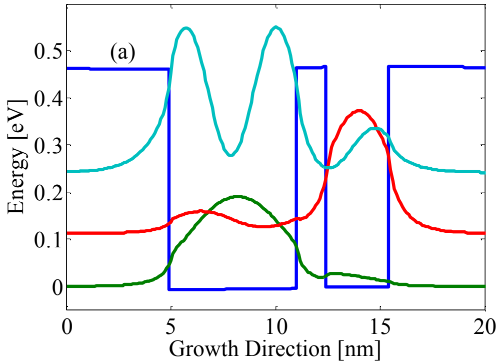
- Strongly coupled structures exhibit large field enhancements – Useful to enhance second harmonic generation in ISTs in QWs



- Doubly resonant metamaterials enhance second harmonic generation

Gorkunov et al. *Appl. Phys. Lett.* **88**, 071912 (2006)
Kanazawa et al. *Appl. Phys. Lett.* **99**, 024101 (2011)

- Design the quantum well to support two ISTs at 30 and 60 THz with large $\chi^{(2)}_{zzz}$



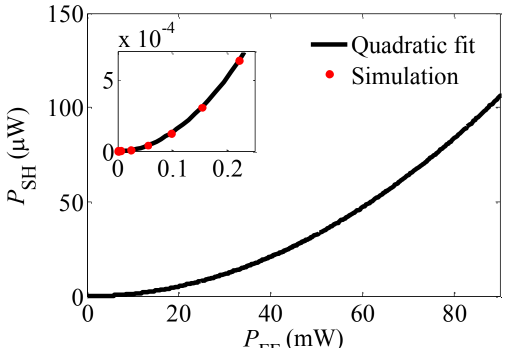
- $\chi^{(2)}_{zzz}$ can be engineered by engineering the overlap between different subbands in the quantum wells

Capasso et al. *IEEE J. Quantum Electron.* **30**, 1313 (1994)

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

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

Second harmonic generation – Results



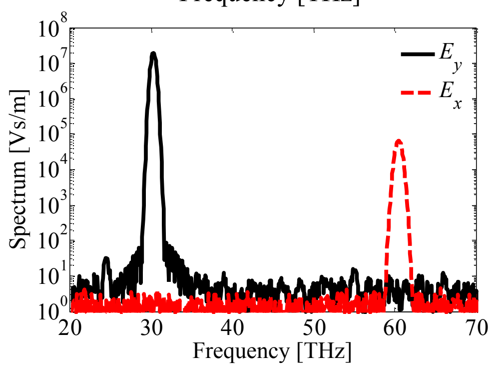
- Signal power at SH frequency shows quadratic dependence as a function of pump power as expected from second order nonlinear process

ThH1.3 9:00 AM – 9:15 AM:

O. Wolf et al.

Second Harmonic Generation in Quantum Wells Enhanced via Coupling to Metamaterials

Frequency [THz]

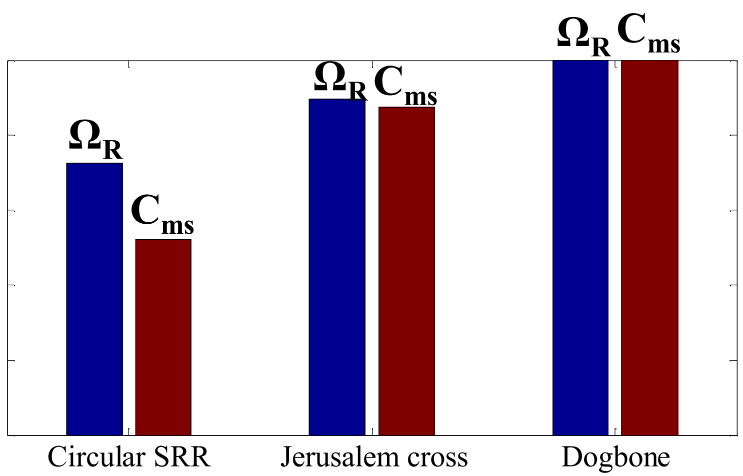


- SH signal is found in **perpendicular** polarization with respect to the pump polarization

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

Summary and conclusions

- Our circuit model shows that increasing the metasurface capacitance C_{ms} induces stronger light-matter interaction



- This may enable us to go beyond strong coupling regime by using planar metamaterials coupled to ISTs in QWs at infrared frequencies

- Such platform is promising for efficient second harmonic generation

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

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

ThH1.3 9:00 AM – 9:15 AM:
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