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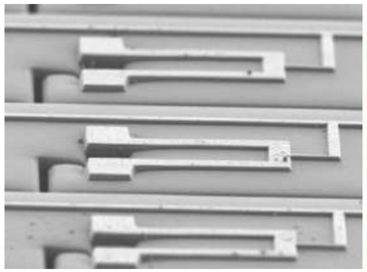
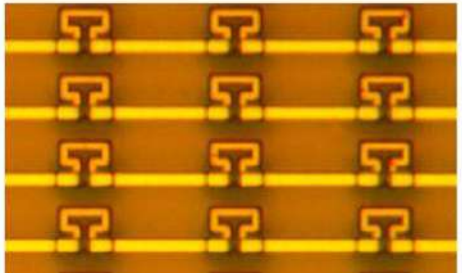
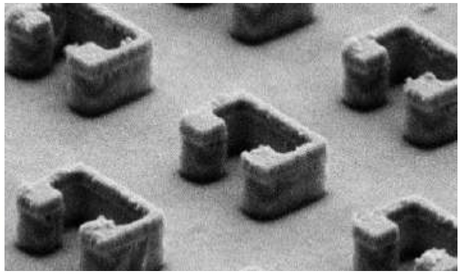
Cavities and metamaterials for infrared optoelectronics: fundamental studies and applications

Yanko Todorov

Laboratoire de Physique et d'Étude des Matériaux (LPEM)
ESPCI, Université PSL, CNRS, Sorbonne Université, Paris, France

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Condensed Matter QED
erc European Research Council Established by the European Commission

Summary

1. Introduction
2. Patch antenna cavities and their applications
3. THz “meta-atoms”

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1. Introduction
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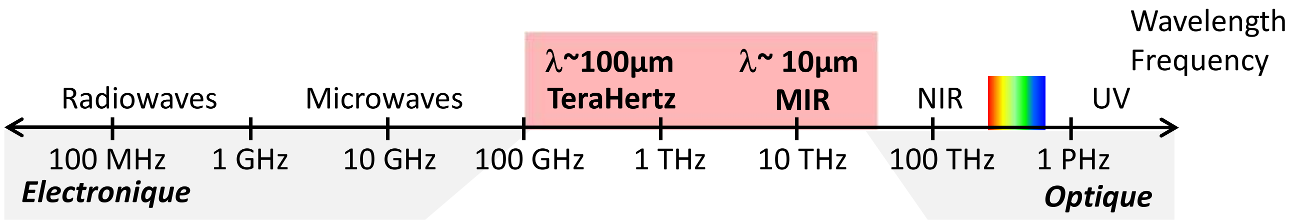
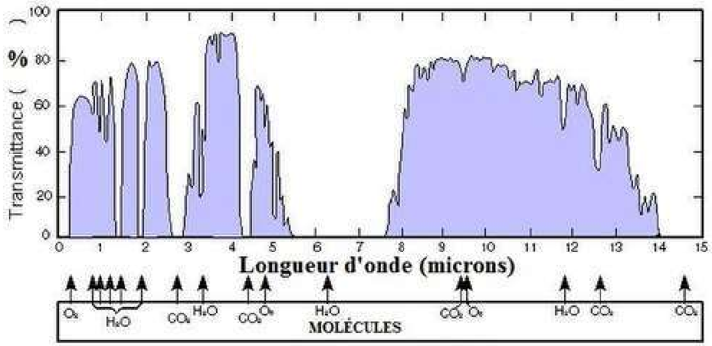
Where am I?



Very wide frequency range, with many applications:

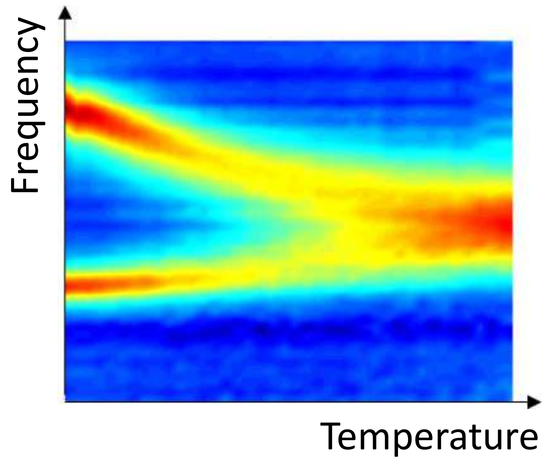
-Thermal imaging
-Non-invasive spectroscopy
-Molecular spectroscopy
-Free space communications
-…



Source: Wikipedia

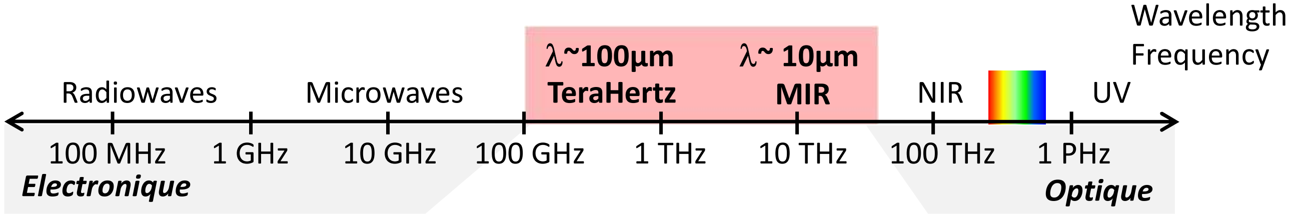
…and playground for fundamental studies

-Ultra-strong light-matter coupling regime



Todorov *et al.* PRL **102**,186402 (2009)

Infrared opto-electronics

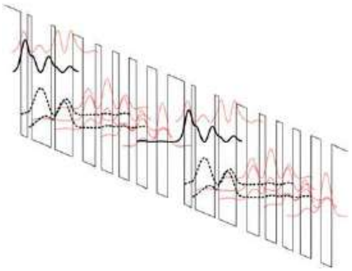


Many technologies to generate & detect such wavelengths:

- Unipolar devices
- Colloidal crystals & MCT
- Type II heterostructures
- Nonlinear conversion
- Gas lasers
- Electronic oscillators (multipliers)
- Bolometers
- Graphene based devices…

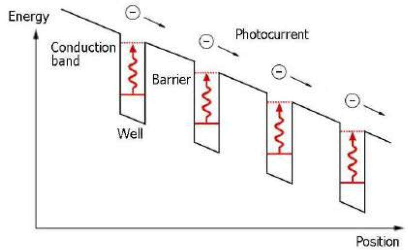
- Quantum cascade laser

(J. Faist, Bell Labs, 1994)



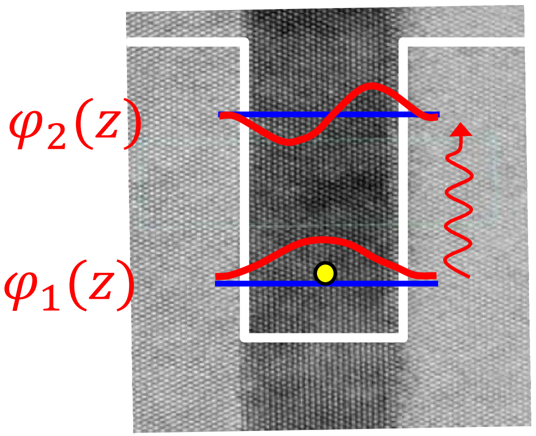
- Quantum well detectors

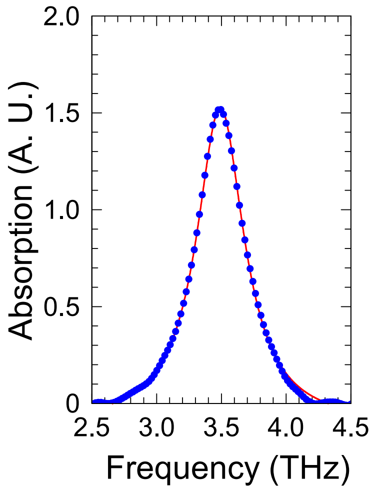
(B. F. Levine, Bell Labs, 1987)



Semiconductor Quantum Well: basic building block

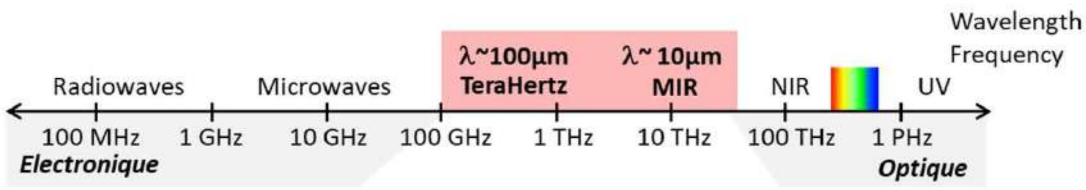
Quantum wells: artificial 1D potentials for electrons





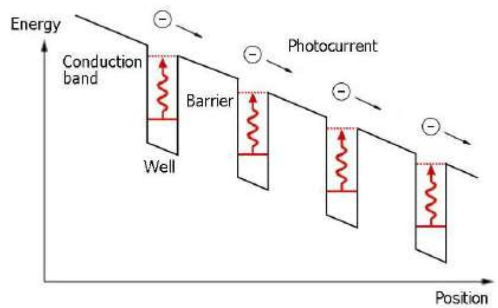
-Transitions can be tuned from MIR to THz

- Design of electronic wavefunctions

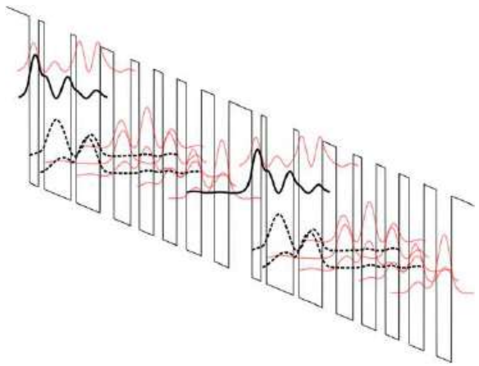


Building blocks for optoelectronic devices in the MIR & THz region

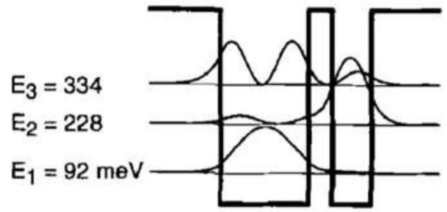
- Quantum well detectors
(B. F. Levine, Bell Labs, 1987)



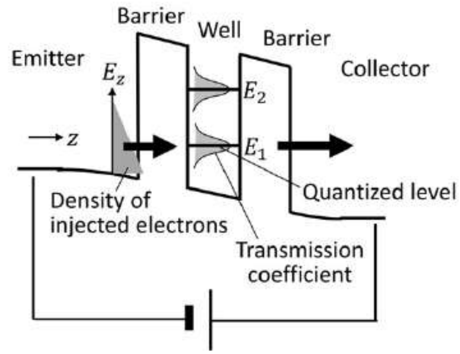
- Quantum cascade laser
(J. Faist, Bell Labs, 1994)



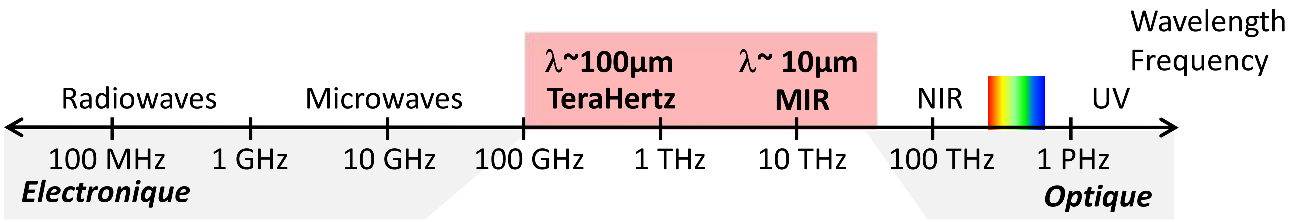
- Nonlinear optics
(C. Sirtori, Bell Labs, 1994)

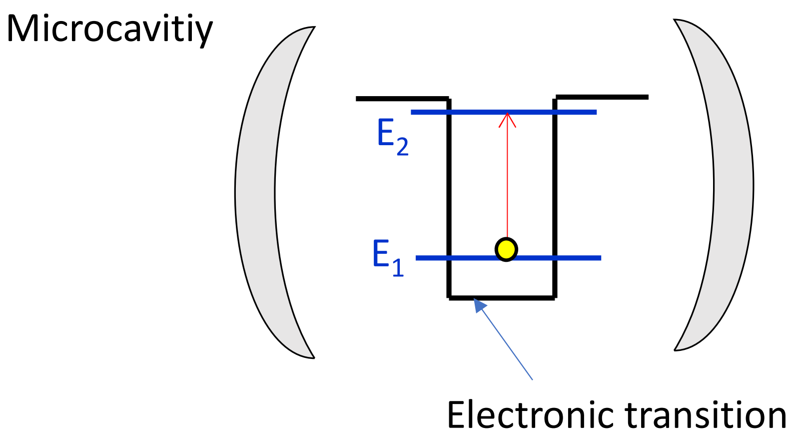


- Resonant-tunneling diodes



“Basic” device architecture





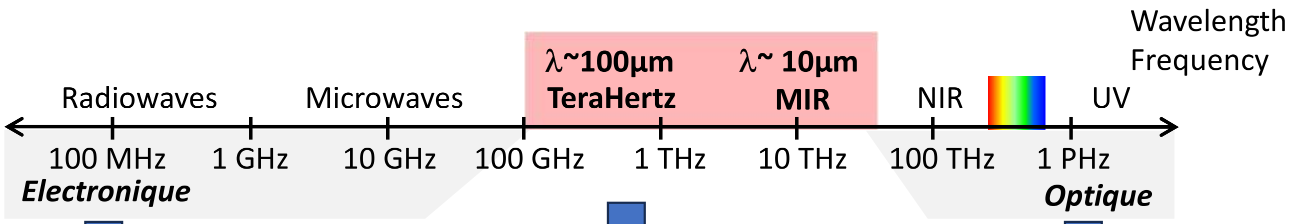
Questions (2000s-2010s):

-What kind of “microcavities”?

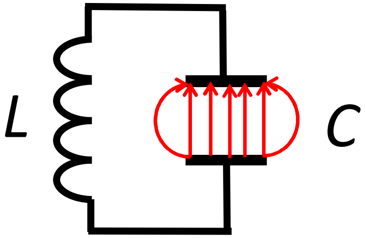
- How to optimize the light-matter interaction in such systems?

-What problems can be solved ?

Well-known objects from electromagnetics

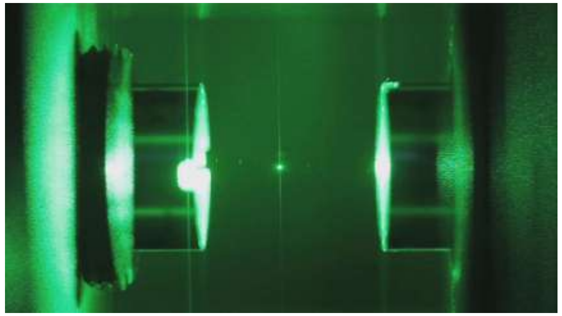


LC Resonator



?

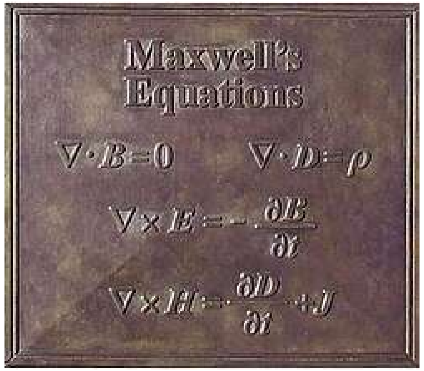
Optical cavity



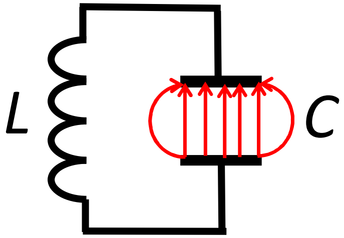
Antenna

Sources: internet

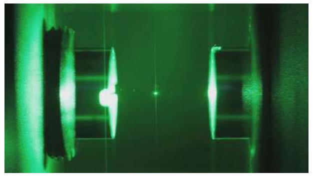
More advanced concepts



LC Resonator

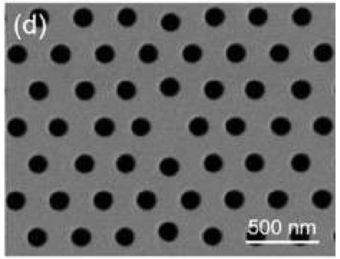


Antenna



Optical cavity

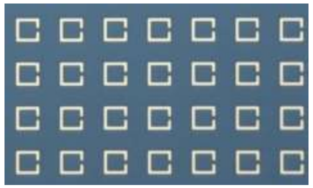
Photonic crystals: *E .Yablonovitch, PRL **58**, 2059 (1987)*



Appl. Phys. Lett. 112, 093101 (2018)

Metamaterials:

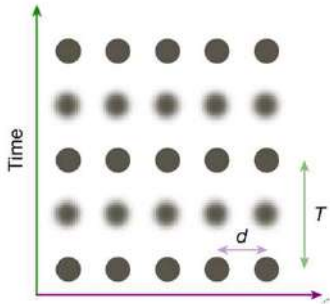
J.B. Pendry, et al., IEEE Trans. Microwave Theory Tech. **47**, 2075 (1999)



Bound states in the continuum (BIC):

C. W. Hsu, et al. Nature Rev. Mat. **1**, 16048 (2016)

Photonic Time crystals:



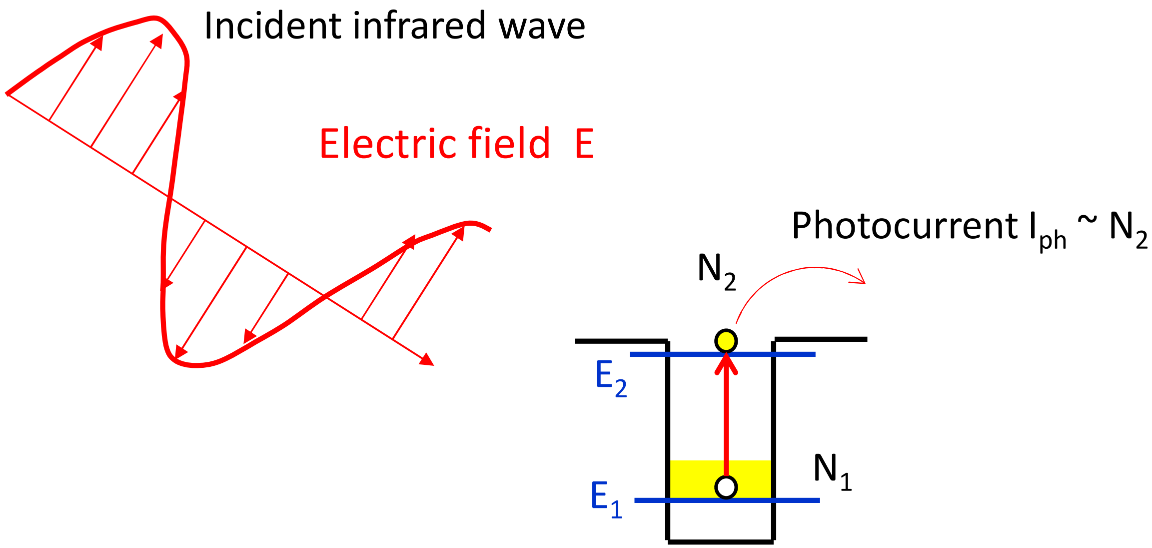
Y. Laplace & coworkers
Nature **656**, 343–348 (2026)

....

Summary

1. Introduction
2. Patch antenna cavities and their applications
3. THz “meta-atoms”

Practical example: let us consider a detector of IR waves



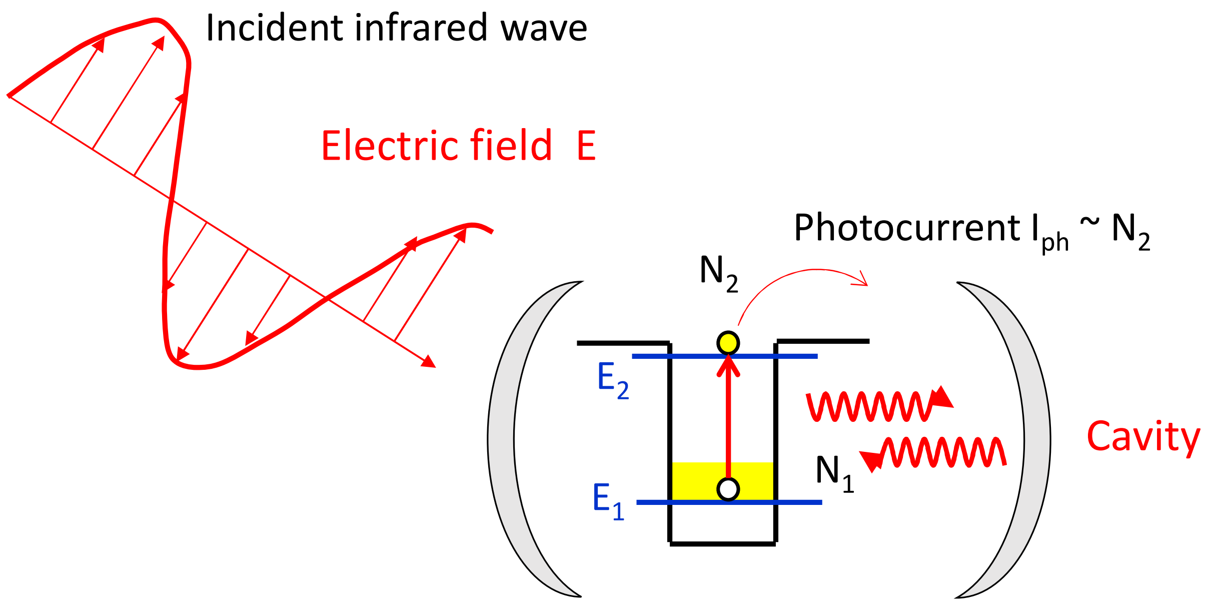
$$N_2 \sim \text{Absorption} \sim N_1 |\boldsymbol{D}_{21}.E|^2$$

Electronic dipole: D_{21}

Electric field around the quantum well

Maximize the electric field !

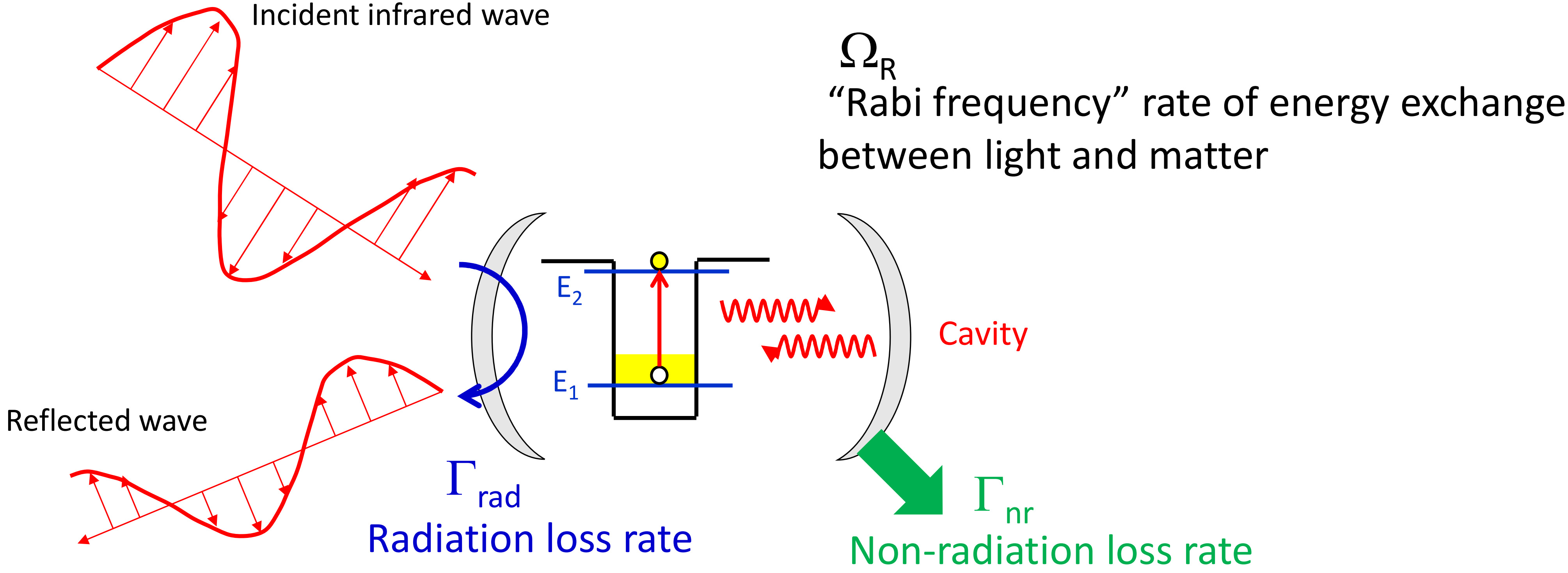
Practical example: let us consider a detector of IR waves



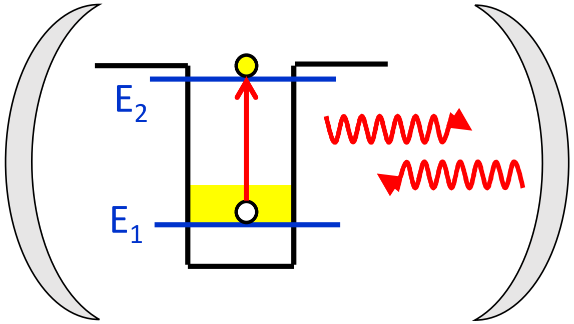
N_2 ~Absorption ~ $N_1 |\boldsymbol{D}_{21}.E_{cav}|^2$

→ Electric field of the cavity: enhancement owe to resonant effects.

Important quantities



Light-matter interaction

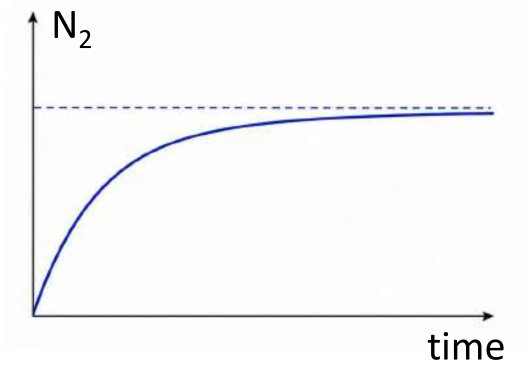


$$\Omega_R = \frac{\sqrt{N_1} D_{12} E_{vac}}{\hbar} \qquad E_{vac} = \sqrt{\frac{\hbar \omega_{cav}}{\epsilon \epsilon_0 V_{cav}}}$$

Effective cavity volume:
Make it as small as possible!

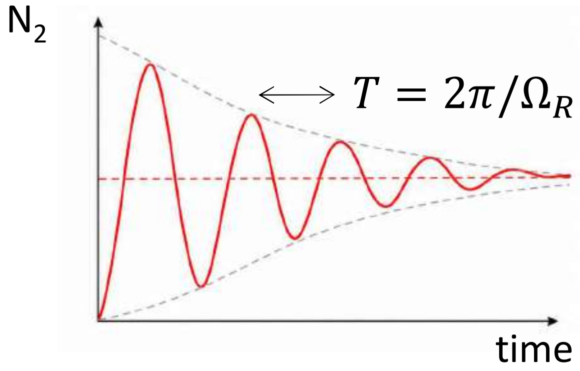
"Weak coupling"

$\Omega_R < \Gamma_r, \Gamma_{nr}$

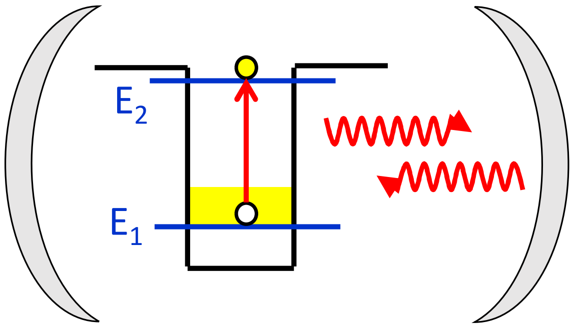


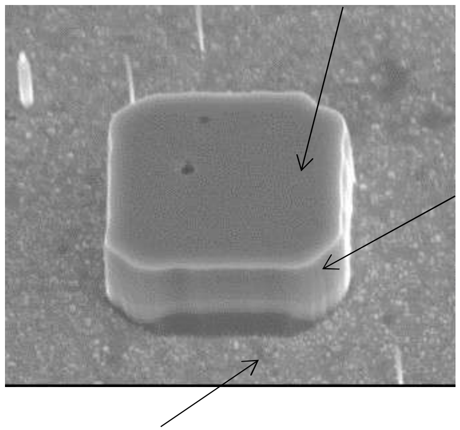
"Strong coupling"

$\Omega_R > \Gamma_r, \Gamma_{nr}$

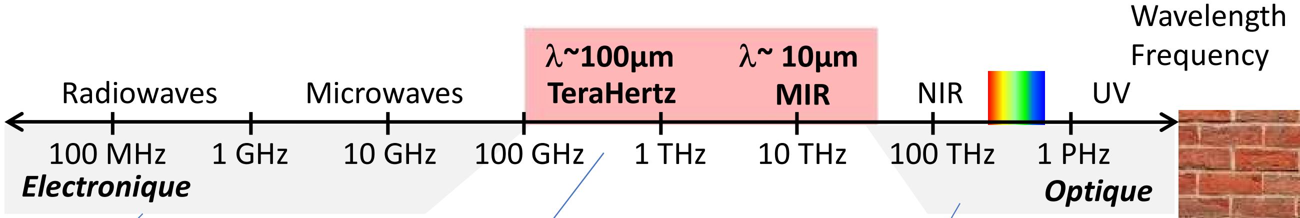


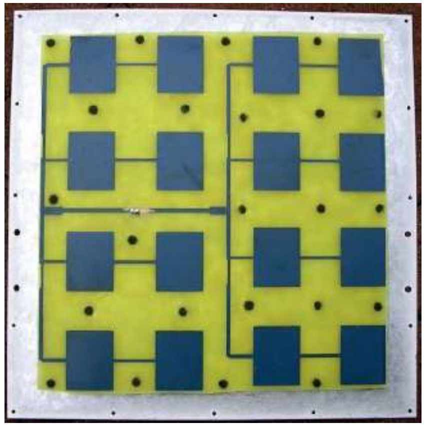
Implementation: Patch antenna cavities



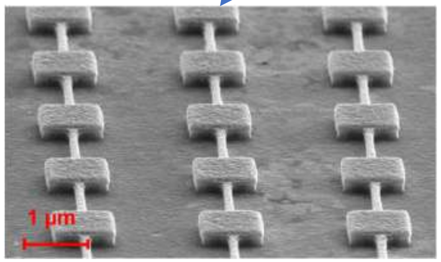


« MIMs » resonators: state of the art

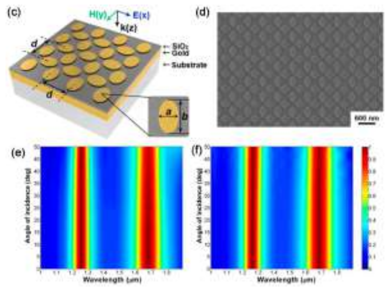




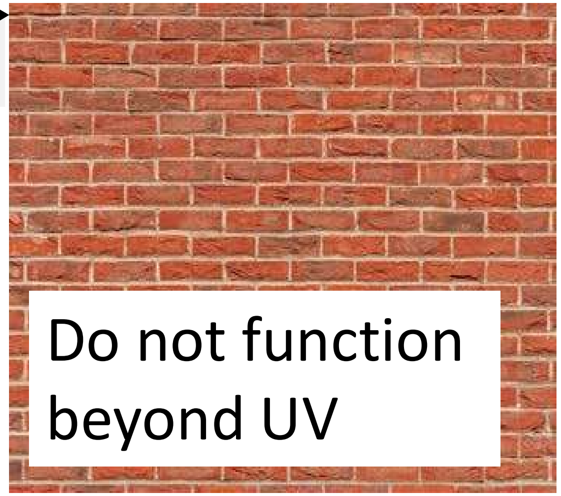
Very common microwave component (antenna function: receivers & emitters)



Optoelectronic applications
Fundamental studies

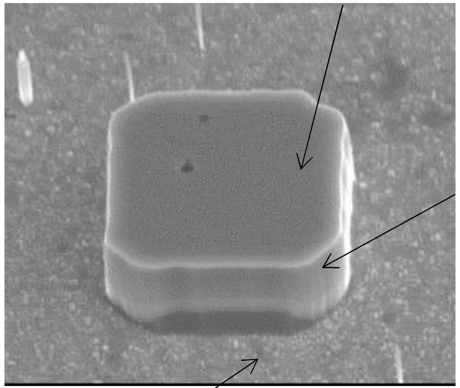


Perfect absorbers
Thermal emission
Photovoltaic devices
…



THz Patch antenna cavities

metal

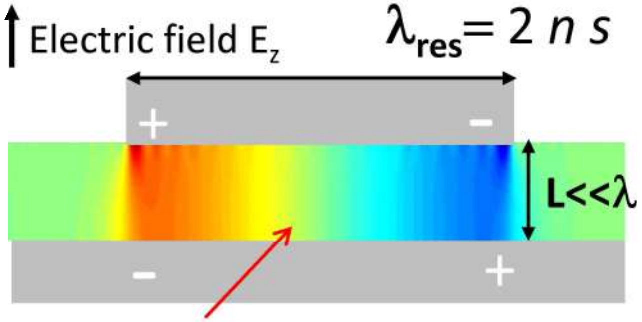


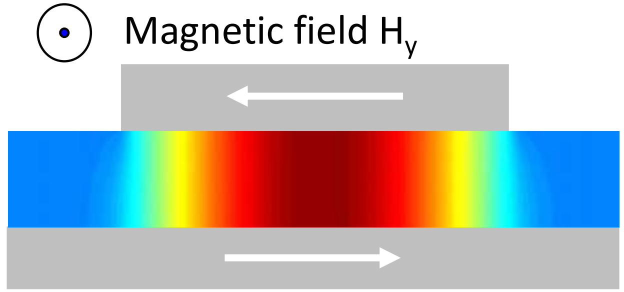
Semiconductor with QWs

metal
"ground"

- **Fundamental mode**

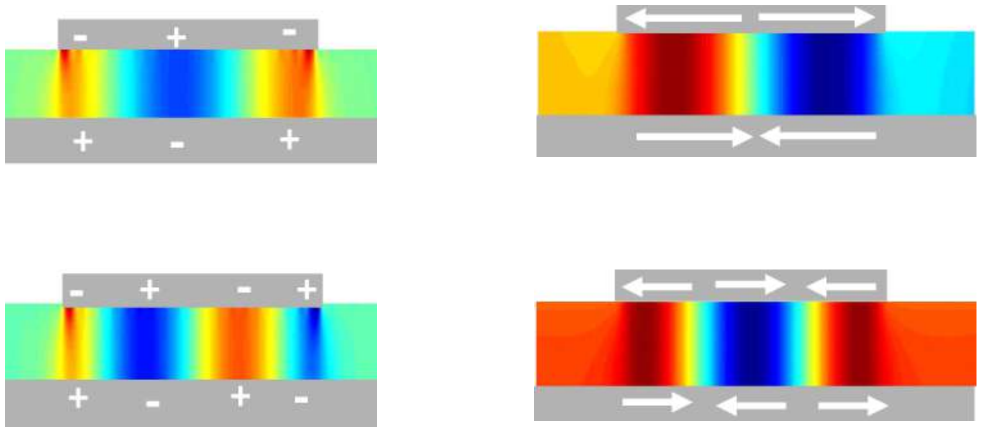
$\lambda_{res} = 2\, n\, s$





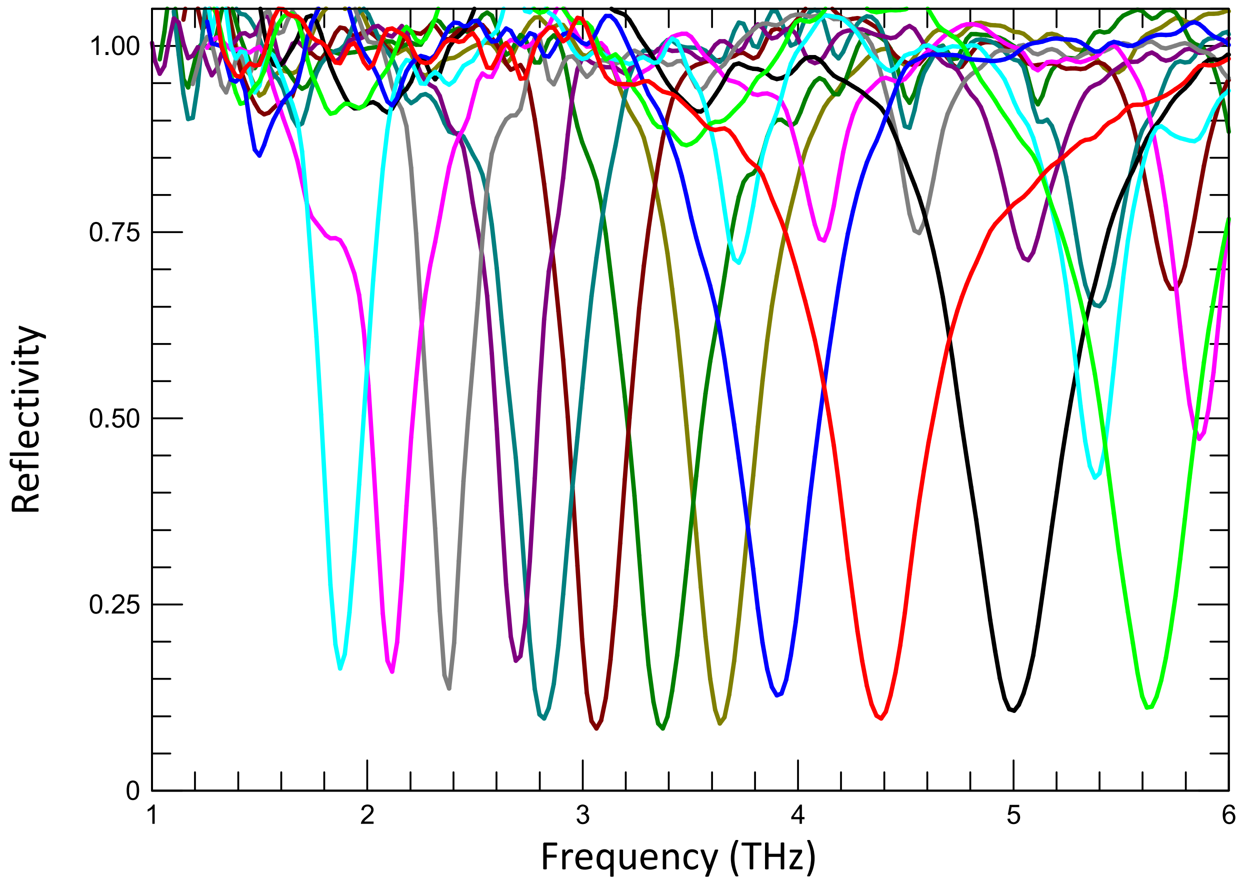
Standing wave

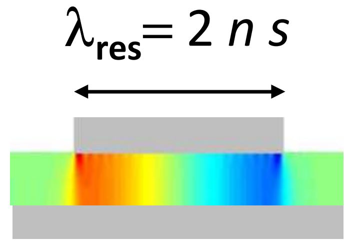
- **High order modes**



JOSA A, **24**(10), 3100-14 (2007)
Opt. Express **18**, 13886 (2010)
PRL **105,** 196402 (2010)

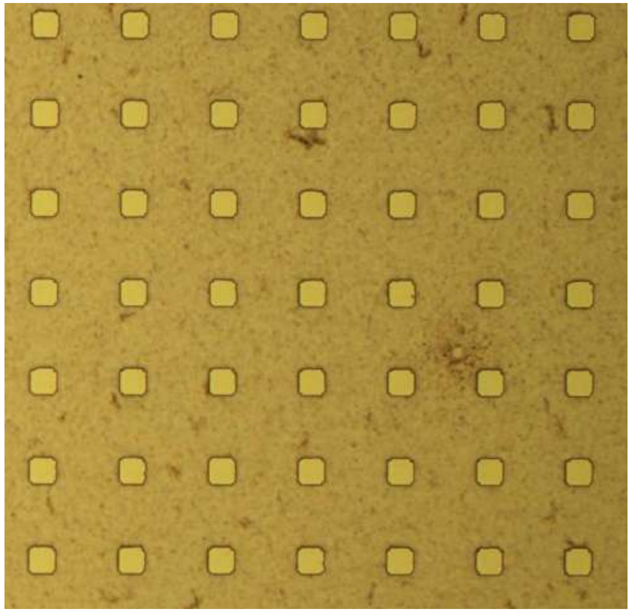
Tuning of the resonant mode

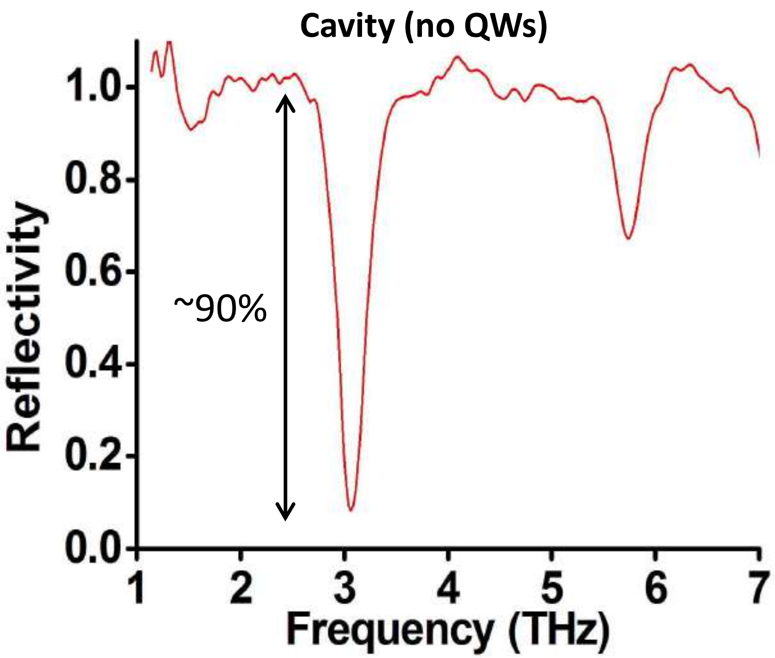




s= 5µm - 20µm

Actual experiments are performed on dense arrays …



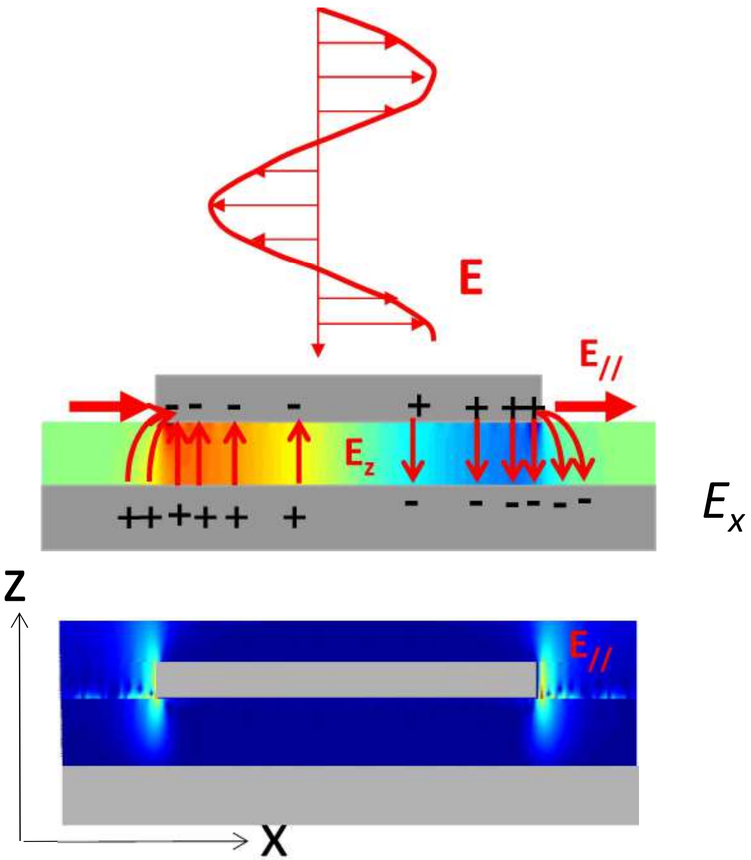


The array configuration is important
In order to increase the
free space coupling rate Γ_{rad} !

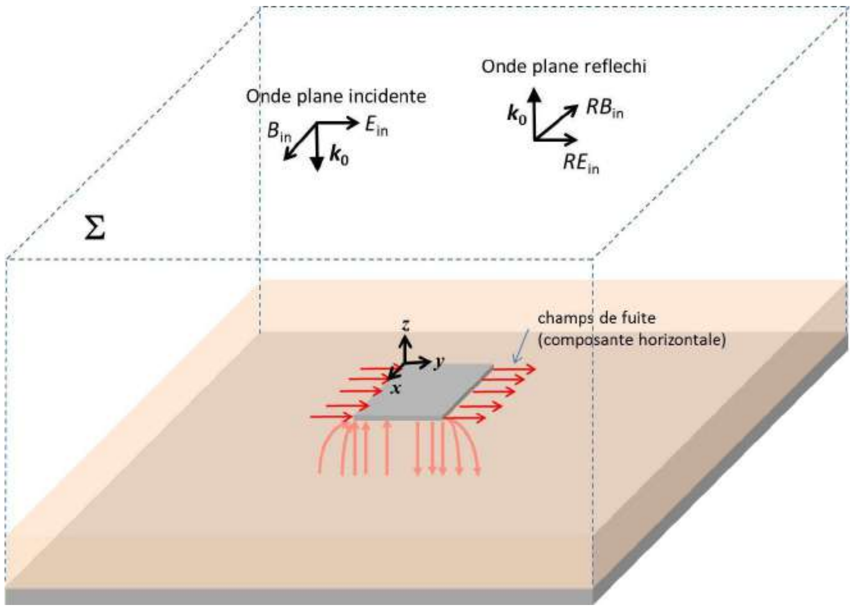
Opt. Express **18**, 13886 (2010)
PRL **105,** 196402 (2010)

Analytical modelling of free space-coupling of the array

- Fringing field paly important role



- Array unit cell



- Electric field of the incident wave is matched to the in-plane fringing fields
- Energy conservation

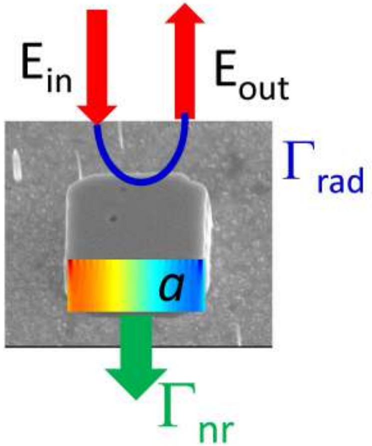
Radiation loss rate:

$$\Gamma_{rad} = \frac{2cL}{n^2\,\Sigma}$$

C. Feuillet-Palma *et al.,* Sci. Rep. **3**, 1361 (2013)

Balanis, C. A. *Antenna Theory* (John Wiley & Sons, 2005).

Analytical modelling of array reflectivity

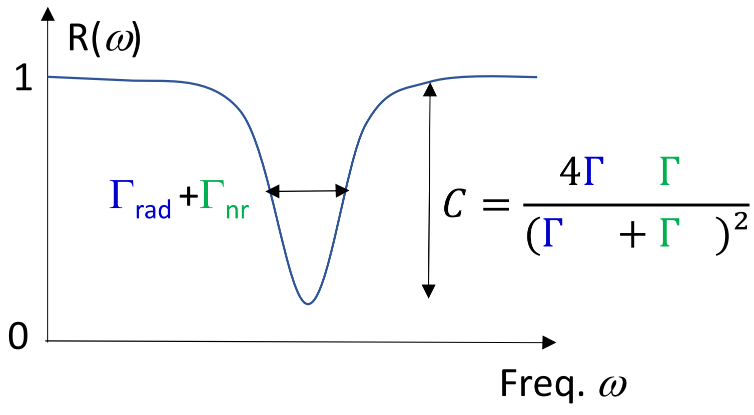


Coupled-mode theory

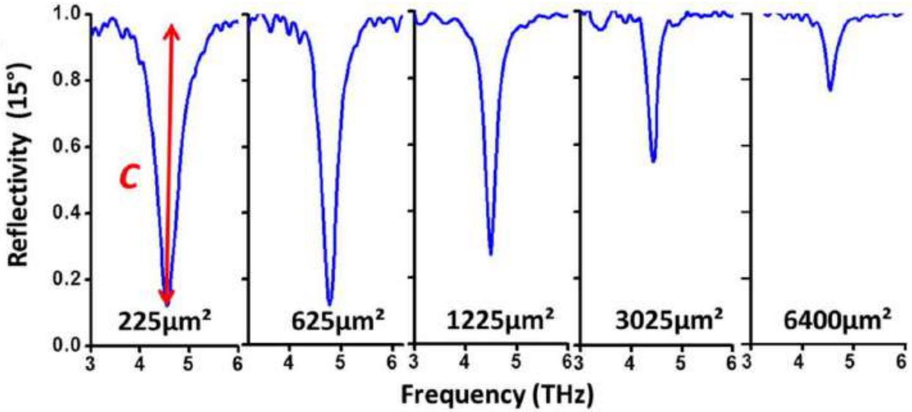
$$\frac{da}{dt} - (i\omega_{cav} - \Gamma_{nr} - \Gamma_{rad})a = \sqrt{2\Gamma_{rad}}\,E$$

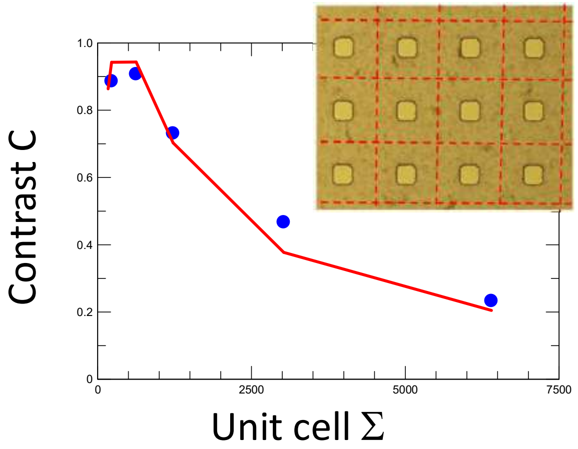
$$E_{out} = -E_{in} + \sqrt{2\Gamma_{rad}}\,a$$

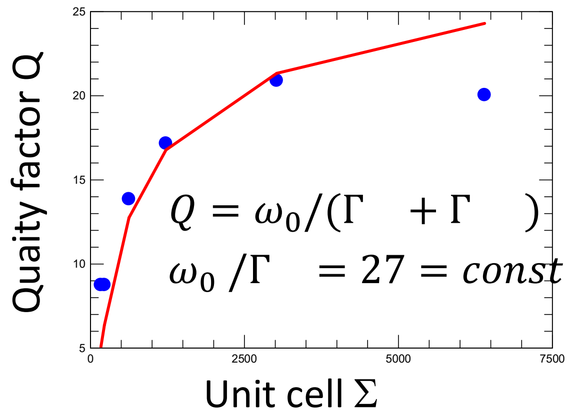
Zanotto et al. Nat. Physics **10**,830 (2014)
M.Jeannin Nano Lett. (2020)
E. Rodriguez et al., Opt. Express (2022)
T. Krieguer et al. Phys. Rev. B (2025)



Array effects

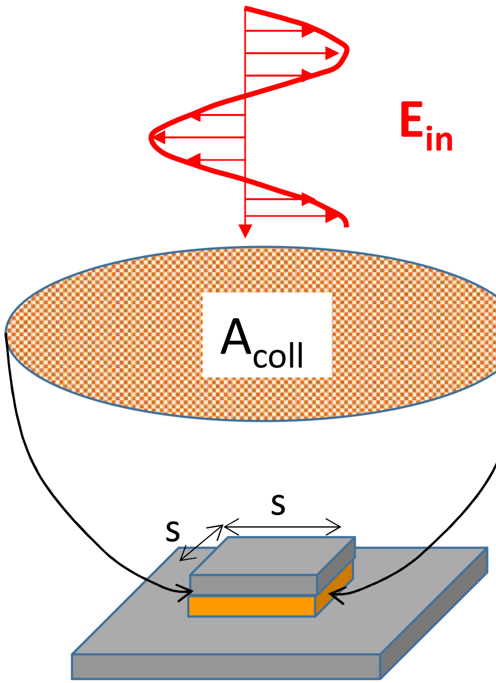


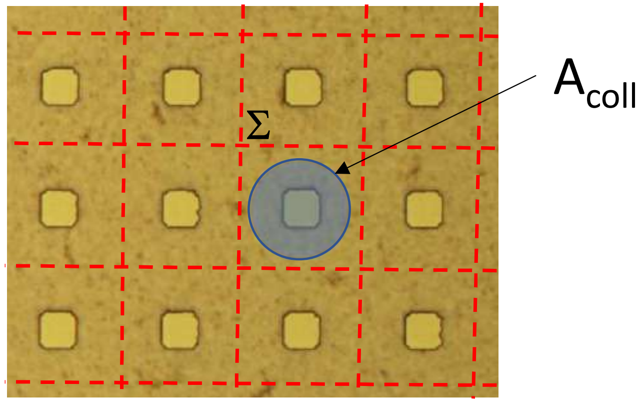




D.Palaferri et al., New J. Phys. **18** 113016 (2016)
E. Rodriguez et al., Opt. Express (2022)

Collection area & Local field enhancement





- Collection area:

Each elements of the array absorb on an effective area:

$$A_{coll}=C\Sigma$$

Typically, A_{coll}~$10xs^2$:
Antenna Effect

- Local field enhancement:

$$\frac{\varepsilon|E_0|^2}{|E_{in}|^2}=\frac{A_{coll}\lambda}{\pi V_{cav}}Q_{nr}$$

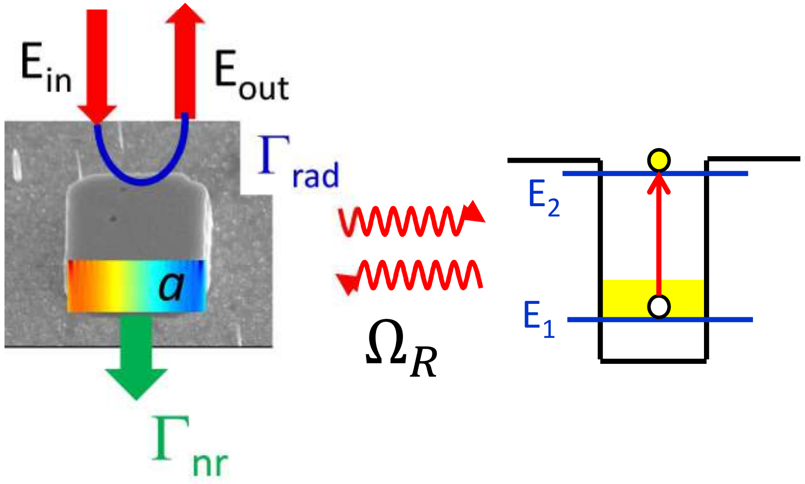
Focusing factor

$$F=\frac{A_{coll}\lambda}{V_{cav}}Q_{nr}$$

D. Palaferri *et al.*, *New Journal of Physics.* **18**, 113016 (2016).

Coupling with quantum wells

Maxwell-Bloch equations (1):



Absorption quantum efficiency

$$N_2 = \eta \, P_{in} \, \tau / \hbar\omega_{21}$$

Population lifetime

$$\eta = \eta \, (\omega, \Omega_R, \Gamma_{rad,} \Gamma_{nr,} \gamma_{21})$$

Decoherence

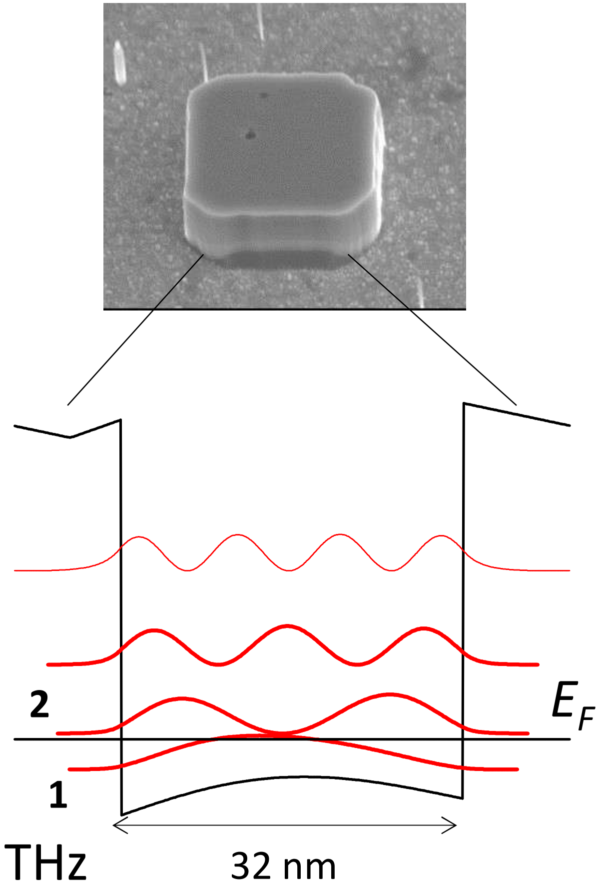
Modelling of:

- Absorption in cavity couped devices (1)
- Saturation (2) and bistability (3,4)
- Non-linear generation (1)
- Advanced modelling of detectors (5)

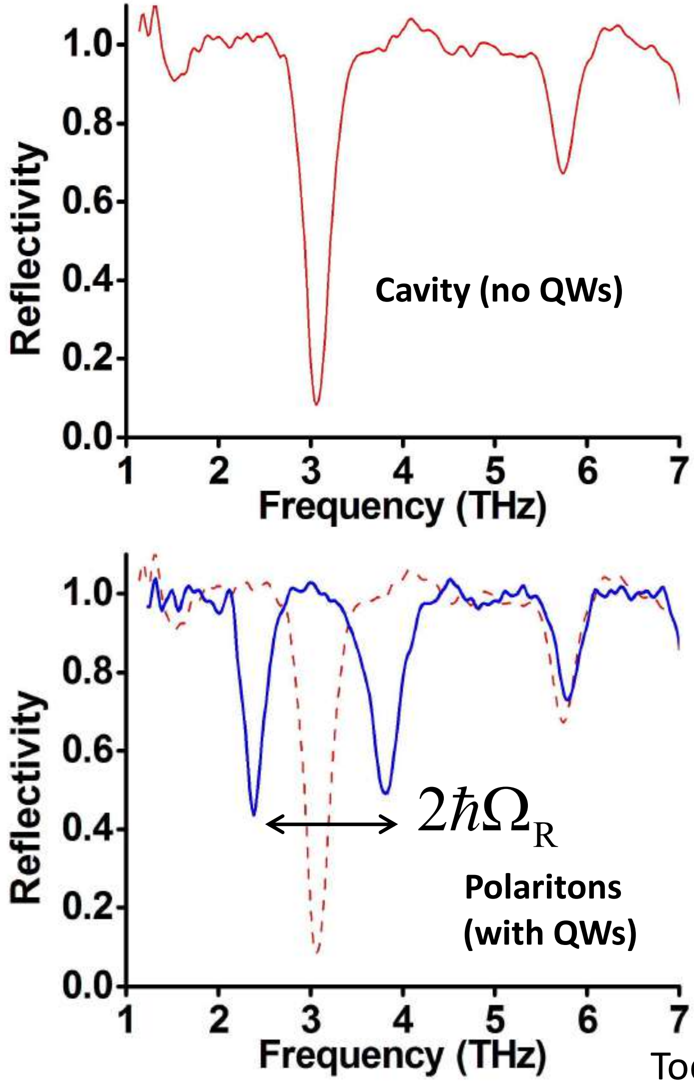
1. T. Krieguer and Y. Todorov , Phys. Rev. B (2025)
2. M. Jeannin, et al. Phys. Rev. Lett. **127**, 187401 (2021)
3. M. Jeannin, et al. APL **122**, 241107 (2023)
4. Lin et al. APL Photonics **10**(4), (2025)
5. Pisani et al. Nature Comm. **14**, 3914 (2023)

Some applications

Ultra-strong light-matter coupling



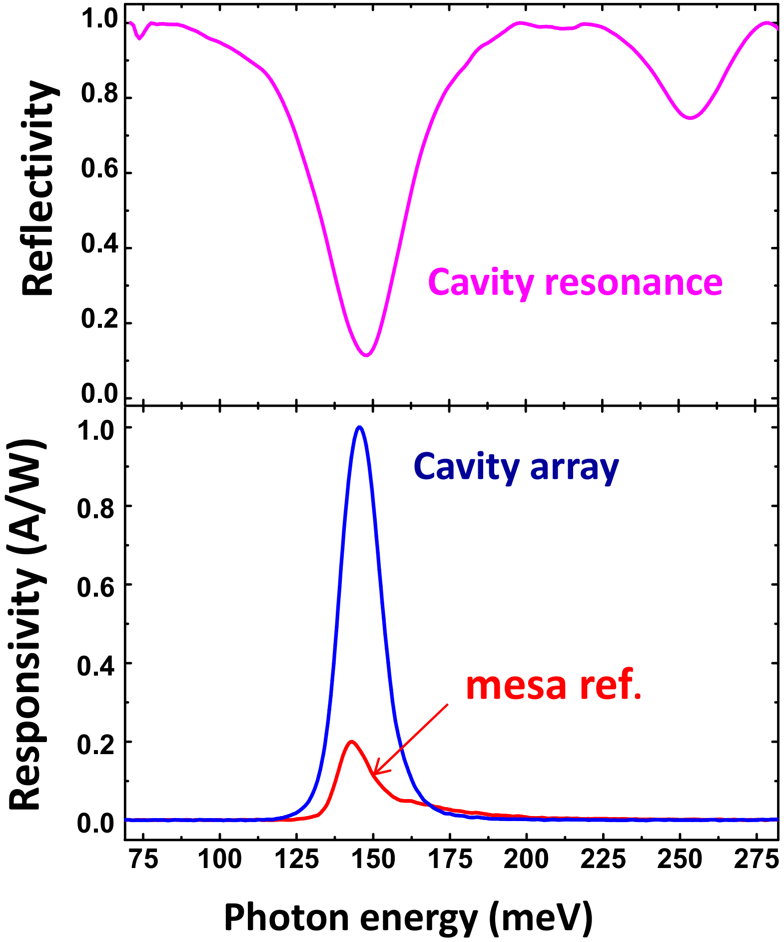
ω_{21} = 3.0 THz



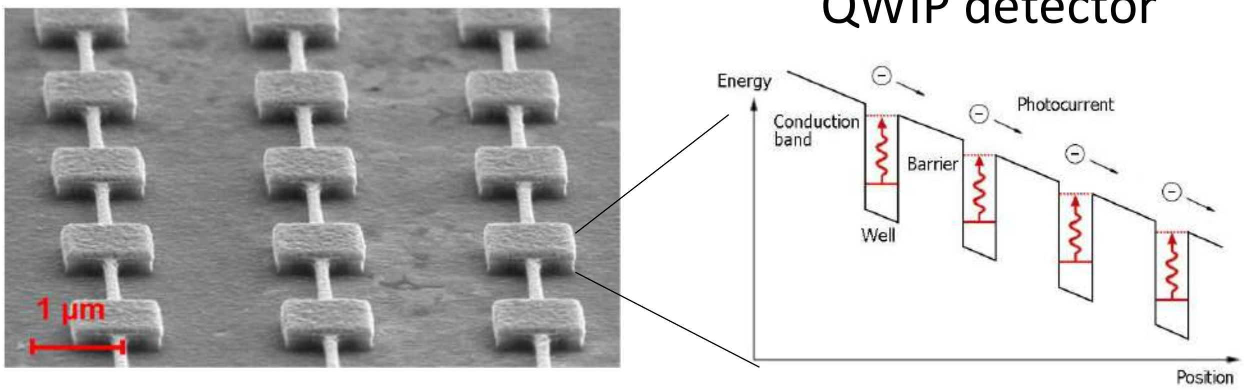
$2\Omega_R / \omega_{21} = 0.46$

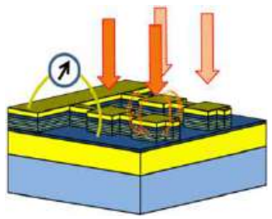
Todorov *et al.* PRL **102**,186402 (2009)
Todorov *et al.* PRL **105,** 196402 (2010)

MIR detectors

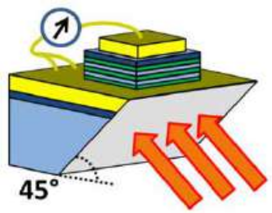


QWIP detector





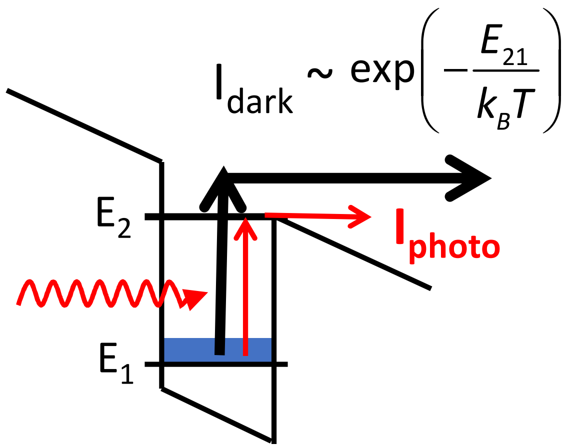
Cavity

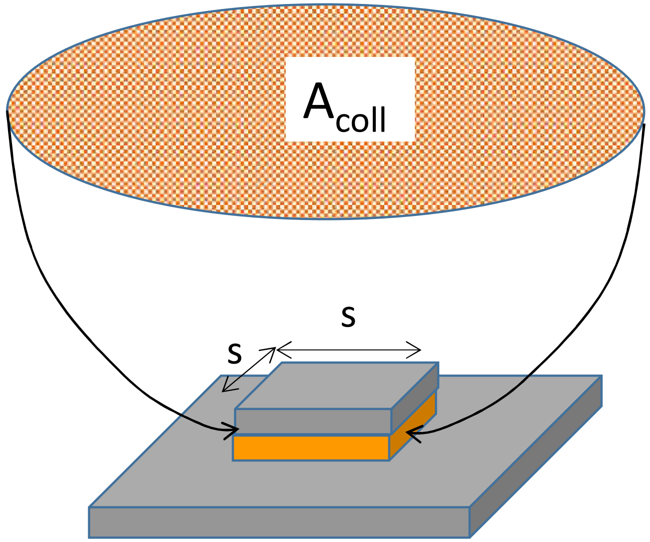


mesa ref.

Y.-N. Chen *et al.* Appl. Phys. Lett. (2014)
D. Palaferri *et al.*, Nature (2018)

Dark current and Antenna effect





Can collect photons from an area larger than the metal pad!

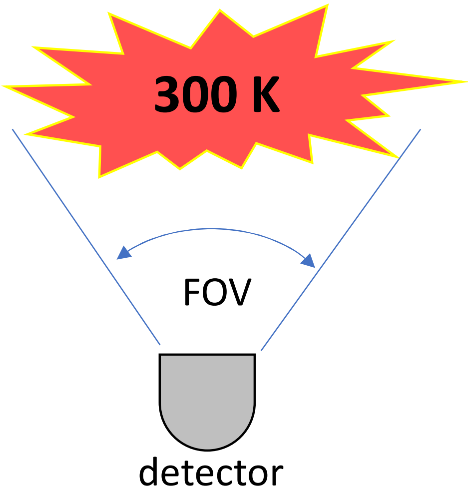
$I_{photo} \sim A_{coll}$ x photon flux

$I_{dark} \sim s^2 \exp(-E_{21}/k_B T)$

-> Increased signal to noise ratio !

D. Palaferri *et al., New Journal of Physics.* **18**, 113016 (2016)

Impact on the temperature performance



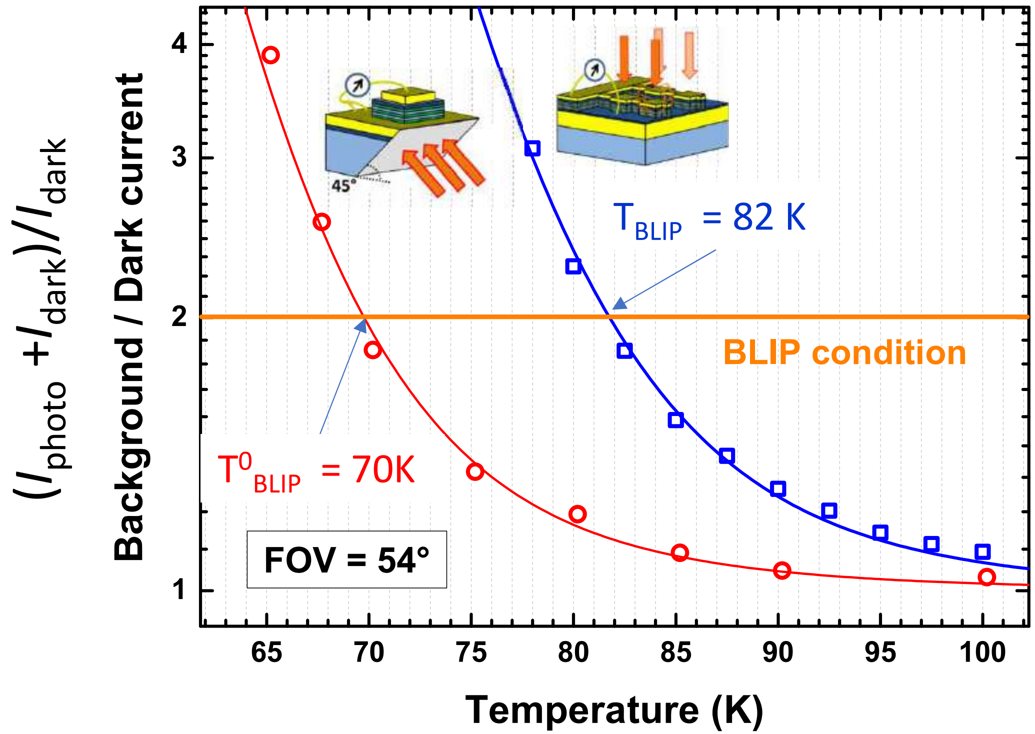
Responsivity

Ambient black body

$I_{photo} = R\Phi_{300K}$

$I_{dark} \sim \exp(-E_{21}/k_B T)$

$I_{photo}(300\text{ K}) = I_{dark}(T_{BLIP})$



Patch antenna detector:

$$T_{BLIP} \approx \frac{T^0_{BLIP}}{1 - \frac{k_B T^0_{BLIP}}{E_{21}}(\ln F - 1.8)}$$

$$F = \frac{\pi\varepsilon |E_{cav}|^2}{|E_{in}|^2} = \frac{A_{coll}\lambda_{res}}{V_{cav}} Q$$

Local field enhancement

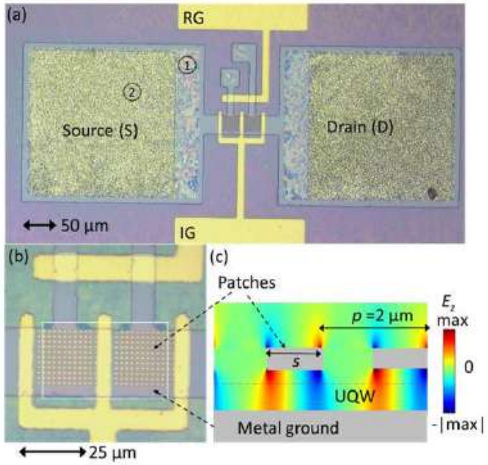
$F \sim 350$

D. Palaferri *et al.*, *Nature* (2018).

Some further developments on patch-antenna coupled devices

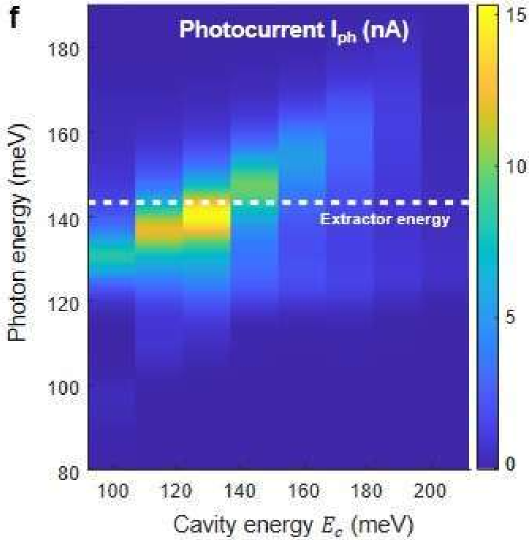
- Enhanced charge sensitive infrared phototransistors

Bahrehmand et al.
Appl. Phys. Lett. **127**, 011103 (2025)



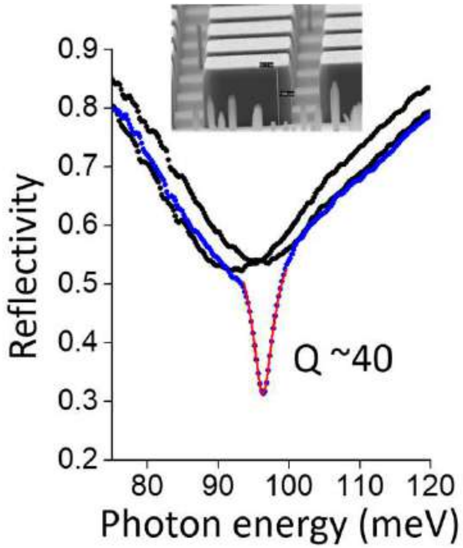
- SC with detectors

Francesco Pisani
(Nat. Comm, 2023)



- BIC in double-metal cavities

Pisani et al.
https://arxiv.org/html/2607.13288v1



ANR PRCI Gerald
Moustapha el Kurdi
PR Telecom Paris

Cavity-enhanced GeSn devices

Other groups (non-exhaustive):

S. Barbieri
High speed and
nonlinear detectors
Appl. Phys. Lett. 120, 091108 (2022)

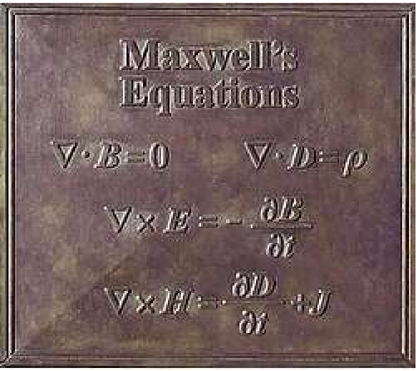
R. Colombelli
Polaritonic modulators
Appl. Phys. Lett. 125, 041101 (2024)

B. Fix and
P. Bouchon
Multispectral IR absorbers,
NL generation, **...**

Y. Laplace
Plasmonic Cavities
Nature **656**, 343–348 (2026)

Summary

1. Introduction
2. Patch antenna cavities and their applications
3. THz “meta-atoms”

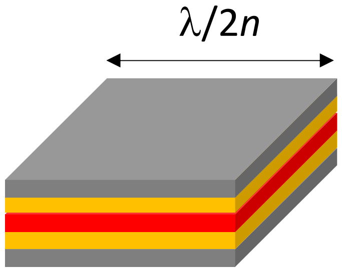


Optics and Electronics

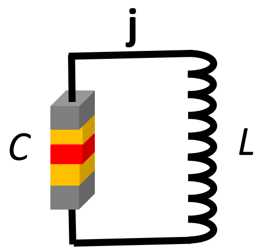
$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{j}$$

displacement current | **real current**

Patch Antenna



Inductor-capacitor circuit



Question:

How can we
Implement
A THz LC circuit?

Optics

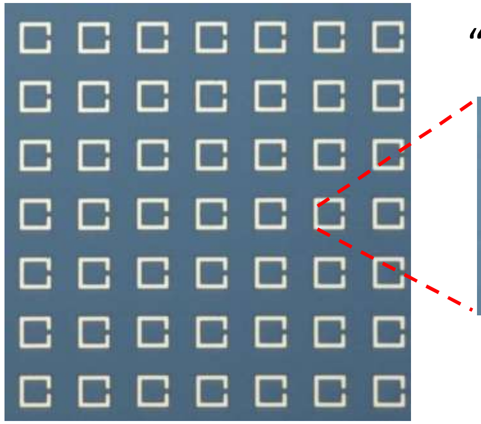
$\sigma \sim (\lambda/2n)^2$

Electronics

$\sigma << (\lambda/2n)^2$

Metamaterials and meta-atoms:

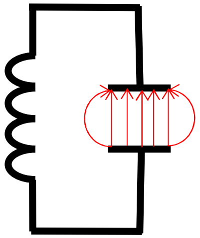
Metamaterials



“meta-atom”

W. Cai and V. M. Shalaev, *Optical Metamaterials: Fundamentals and Applications* (Springer, 2009).

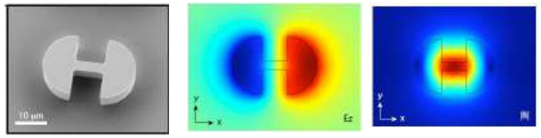
J.B. Pendry, A.J. Holden, D.J. Robbins, and W.J. Stewart, IEEE Trans. Microwave Theory Tech. **47**, 2075 (1999)”.



strong electric field in the capacitor

Implementations in the THz & MIR:

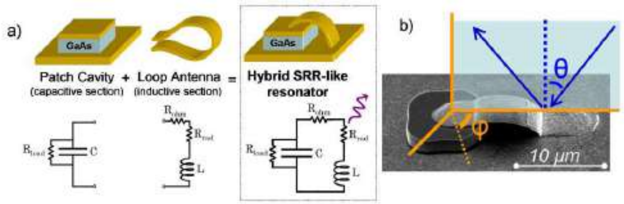
- LC-like patch cavities



C. Walther *et al.* Science (2010)

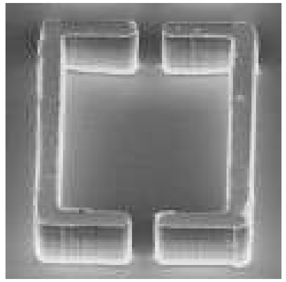
J. Faist’s group (ETH Zurich)

- « Inverted » meta-materials

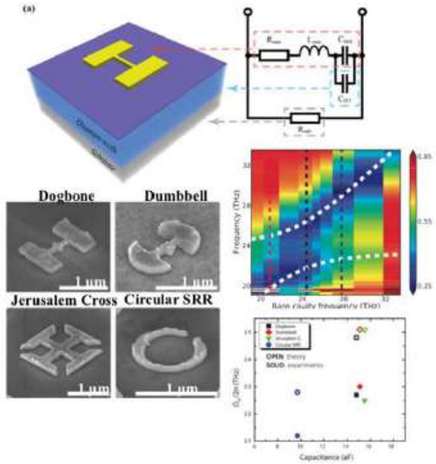


B. Paulillo et al. Opt. Express, **22**, 21302 (2014)

B. Paulillo et al. (2016) “Terahertz meta-atom quantum well photodetectors” Lasers and Electro-Optics (CLEO), USA 2016



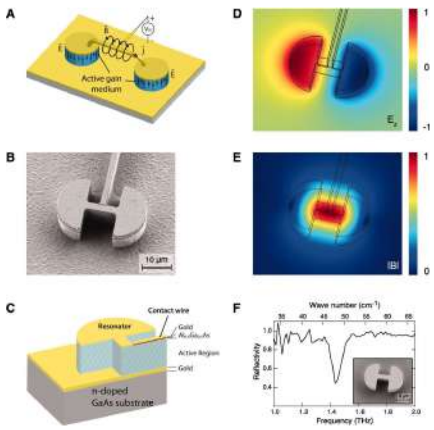
D. Dietze, et al.
Appl. Phys. Lett. 103, 201106 (2013)



Igal Brener’s group, Sandia Labs

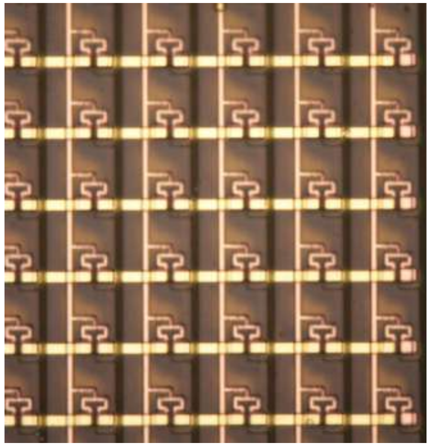
Some THz (LC) meta-atoms:

Quantum cascade lasers



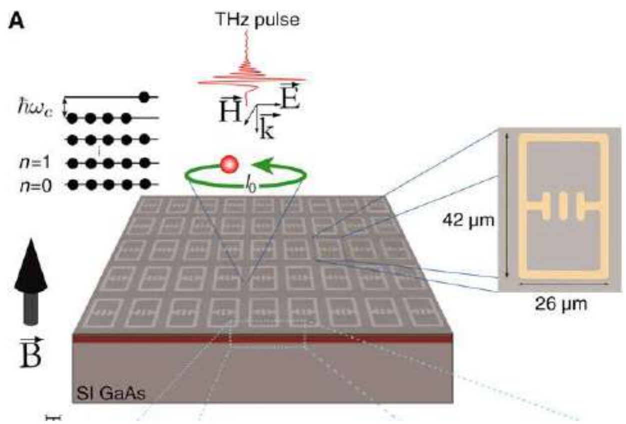
C. Walther *et al.*
Science (2010)

THz detectors



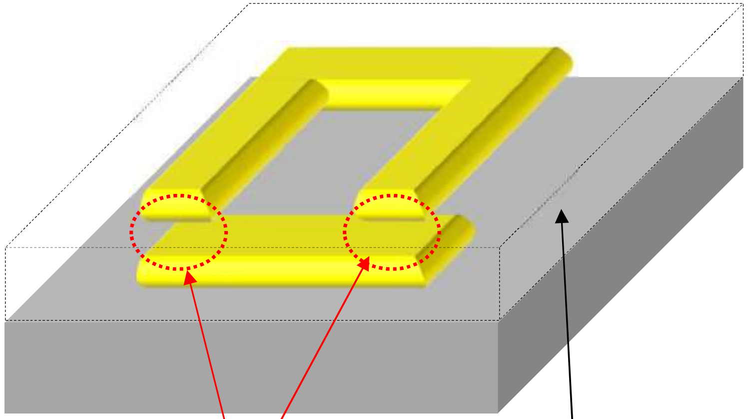
Jeannin et al.,
Appl. Phys. Lett. **117**, 251102 (2020)

Ultra-strong light-matter coupling



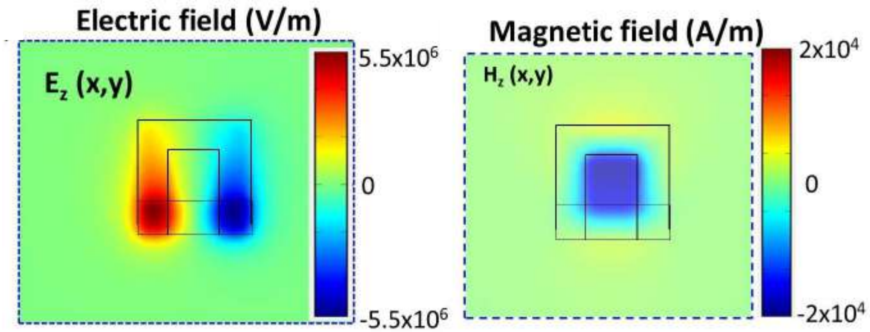
Scalari *et al.*
Science (2012)

The idea

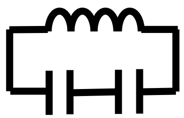


Advantages:

- Highly sub-wavelength confinement
- Propagation effects minimized
- Easy implementation of DC electrical pump/read-out

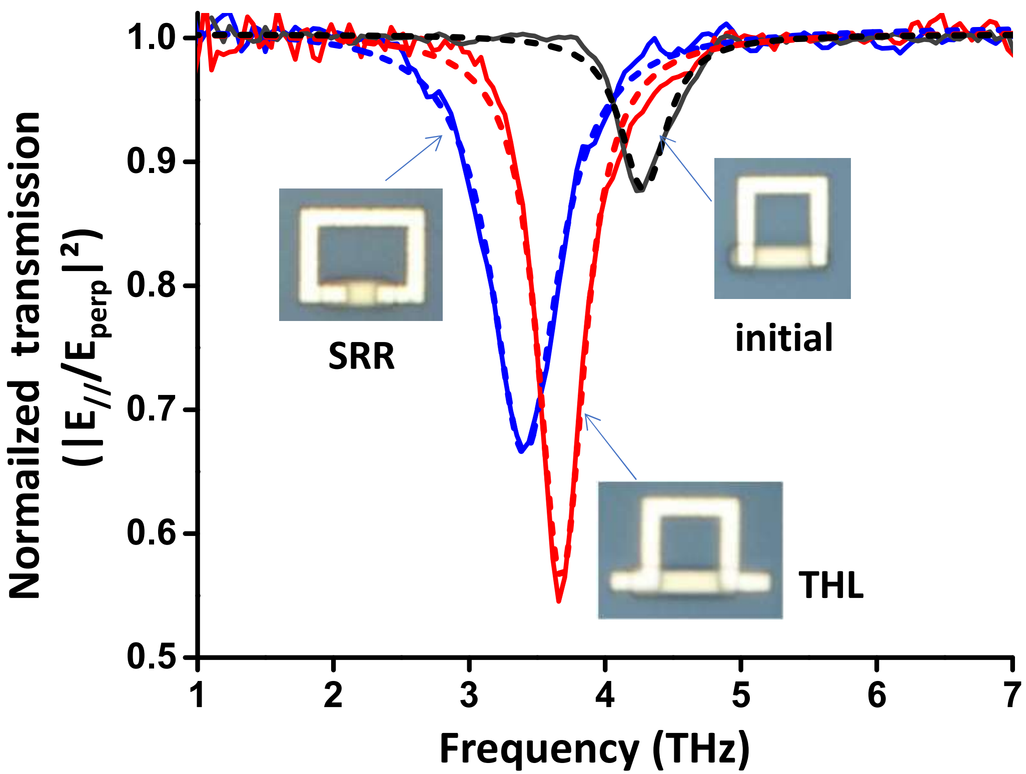


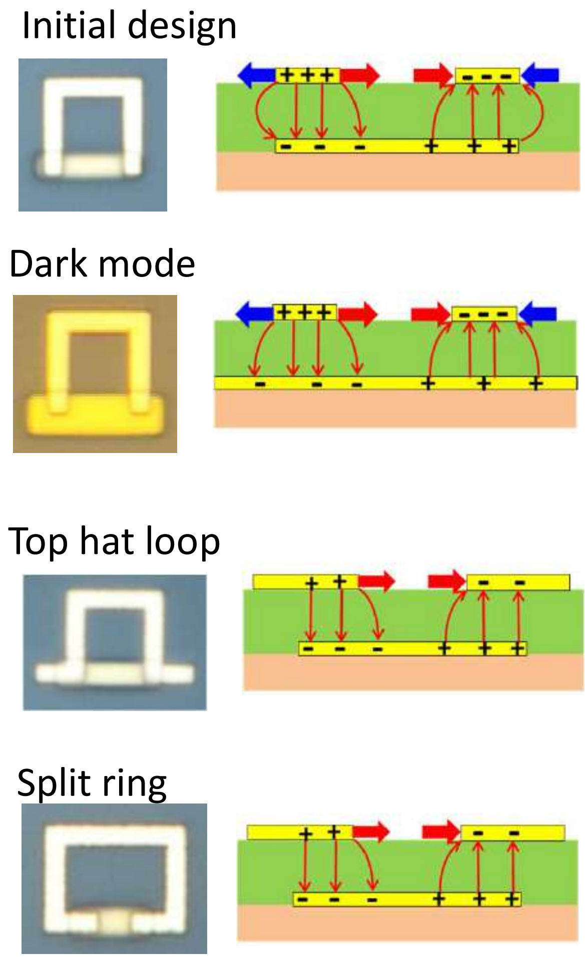
Equivalent circuit:



Y. Todorov, *Opt. Express*. **23**, 16839-16845 (2015)
A. Mottaghizadeh, *Opt. Express*. **25** , 28718-28730 (2017)
O. Mitrofanov, *Opt. Express*. **26** 7437-7450 (2018)

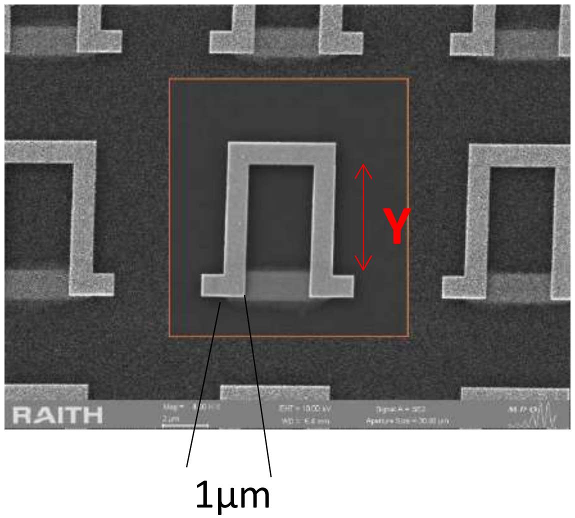
Geometrical explorations

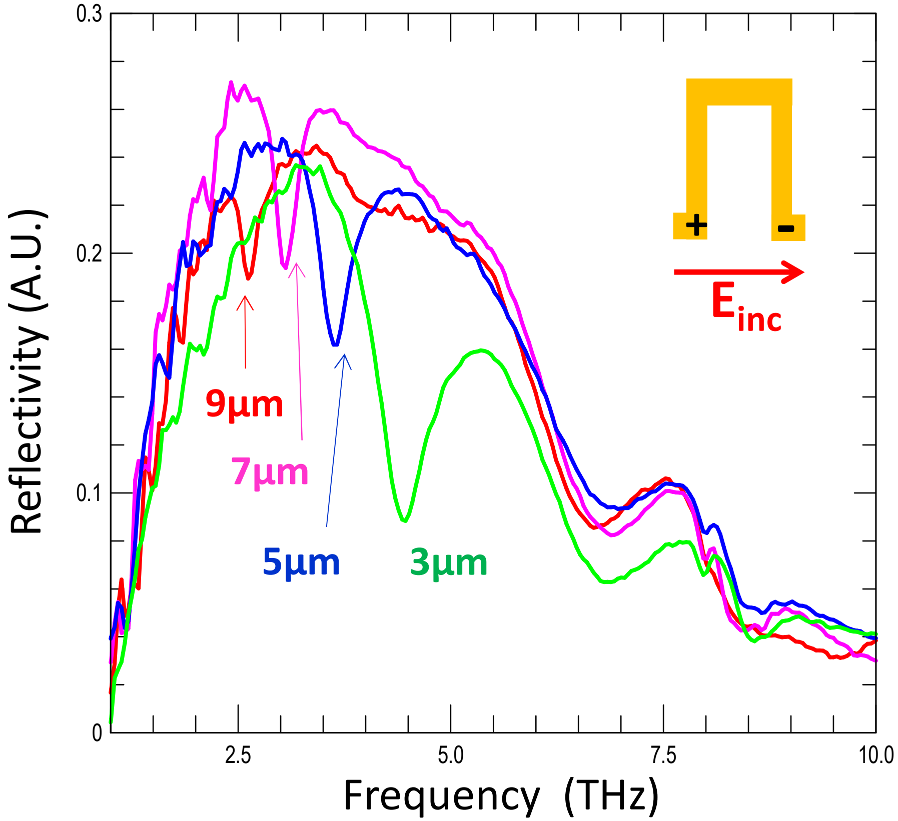




A. Mottaghizadeh, *Opt. Express*. **25** , 28718-28730 (2017)

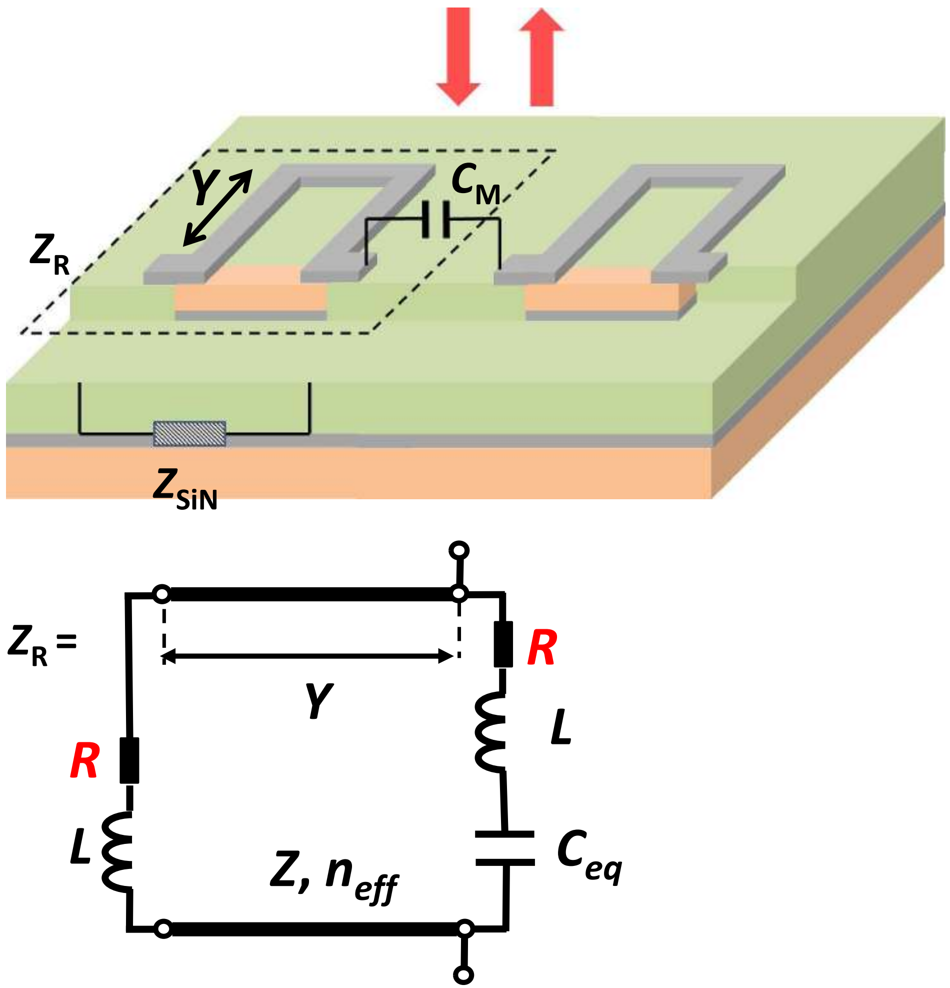
Resonance tuning





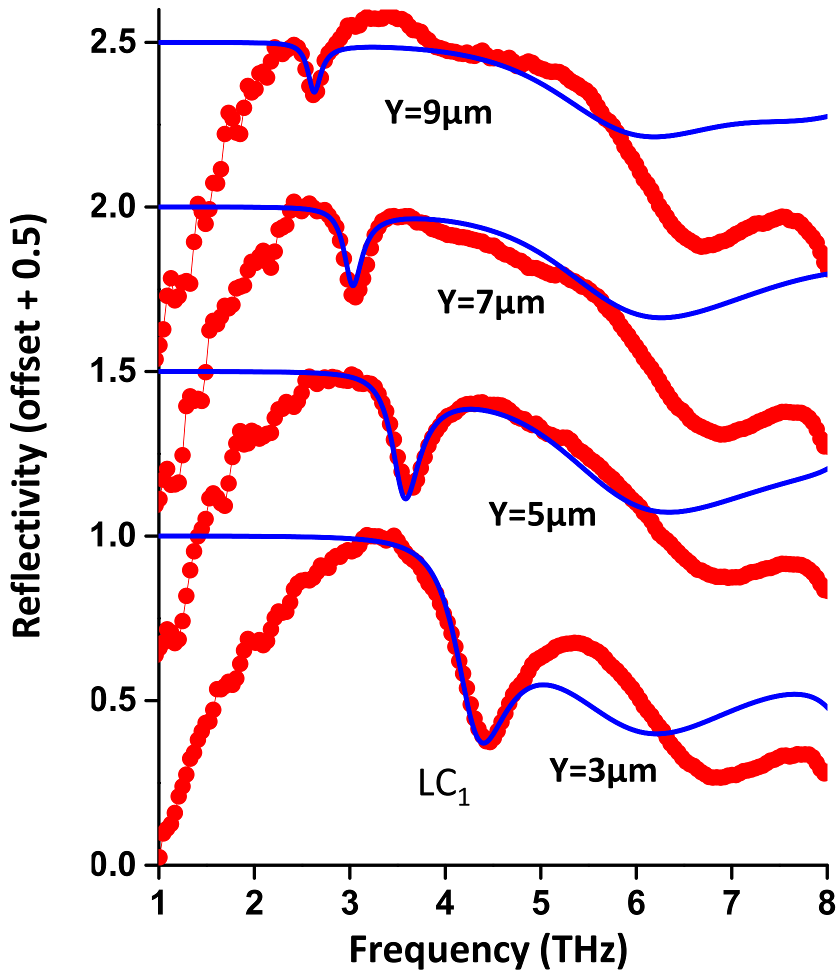
M. Jeannin et al., Optics Express **28**, 16982-16995(2020)

Equivalent circuit model

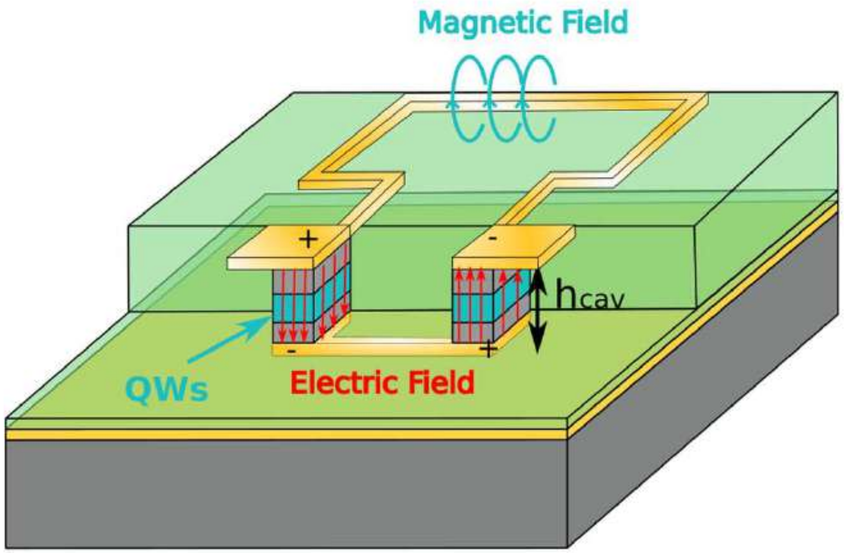


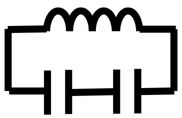
M. Jeannin et al., Optics Express **28**, 16982-16995(2020)

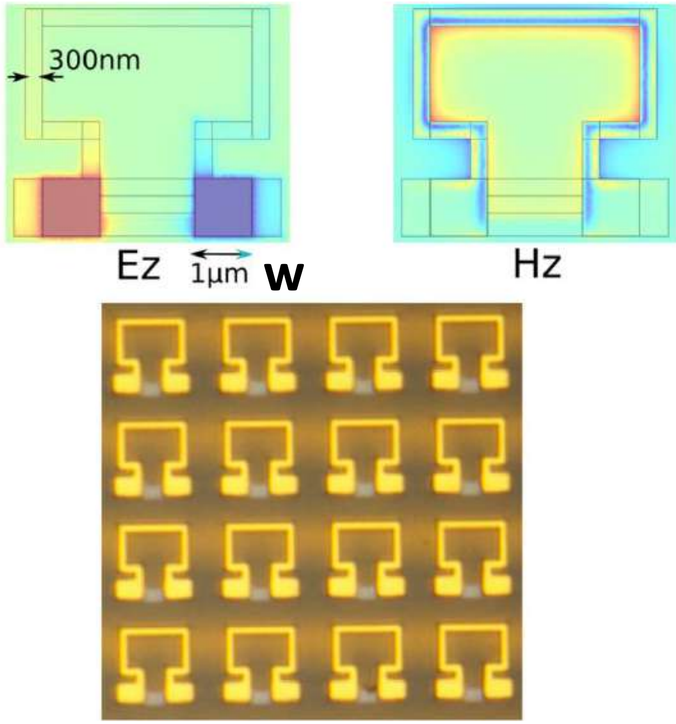
Resonator non-radiative loss dominated by the resistance of the inductive elements!



An optimized THz LC meta-atom



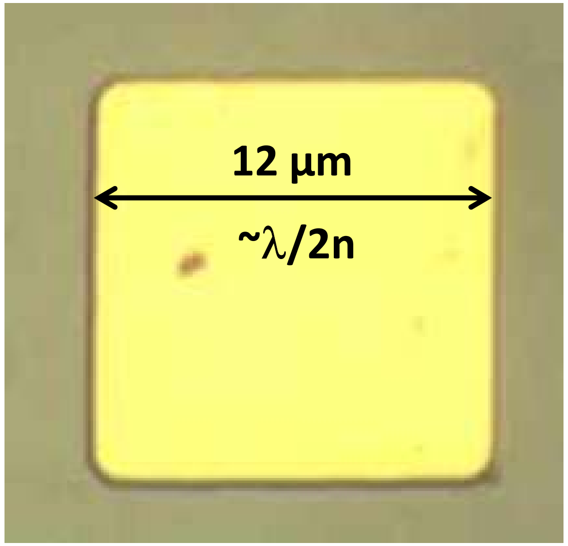
Equivalent circuit: 



M. Jeannin et al. ACS Photonics **6** (5), 1207-1215 (2019)

Comparison with patch-antennas

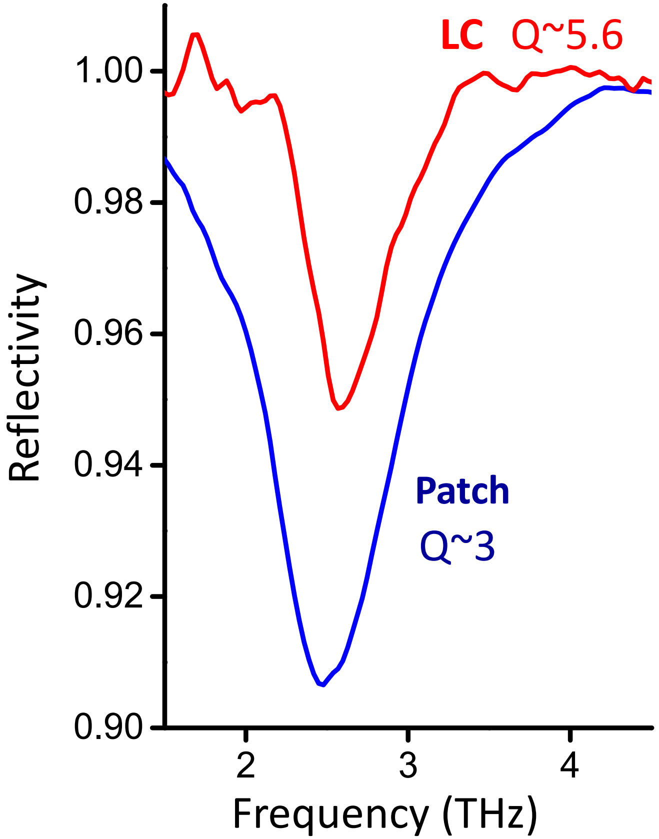
Patch microcavity



V=43μm^3

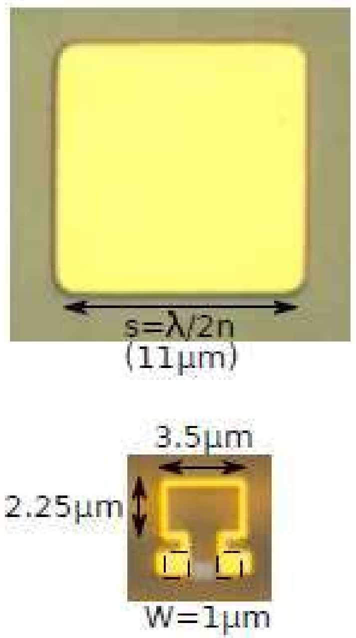
LC

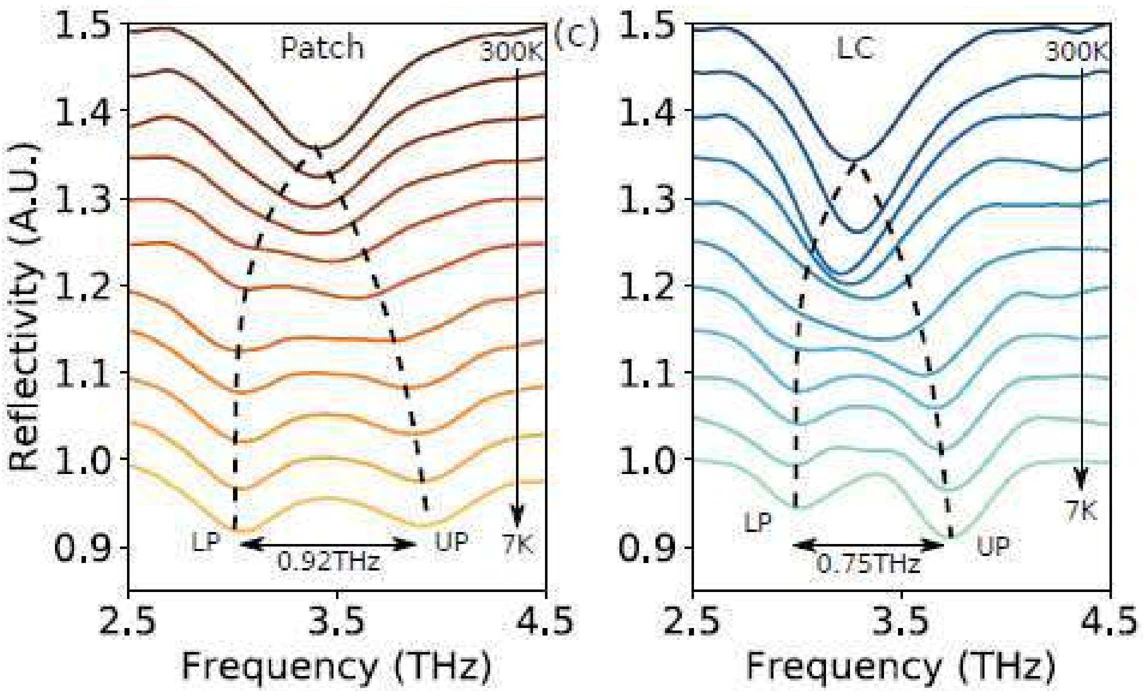
V=0.6μm^3



M. Jeannin et al. ACS Photonics **6** (5), 1207-1215 (2019)

Polariton splitting: attesting the subwavelength confinement

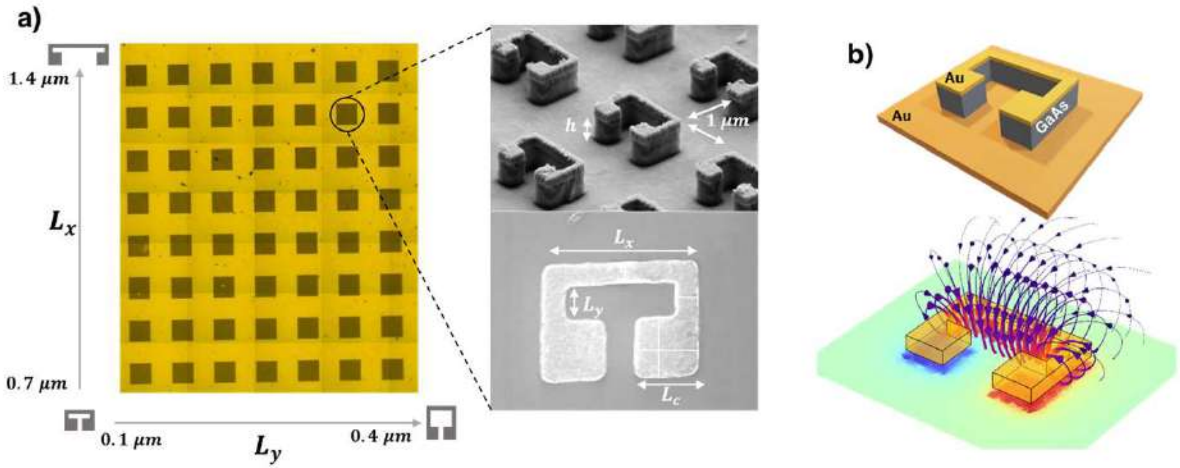


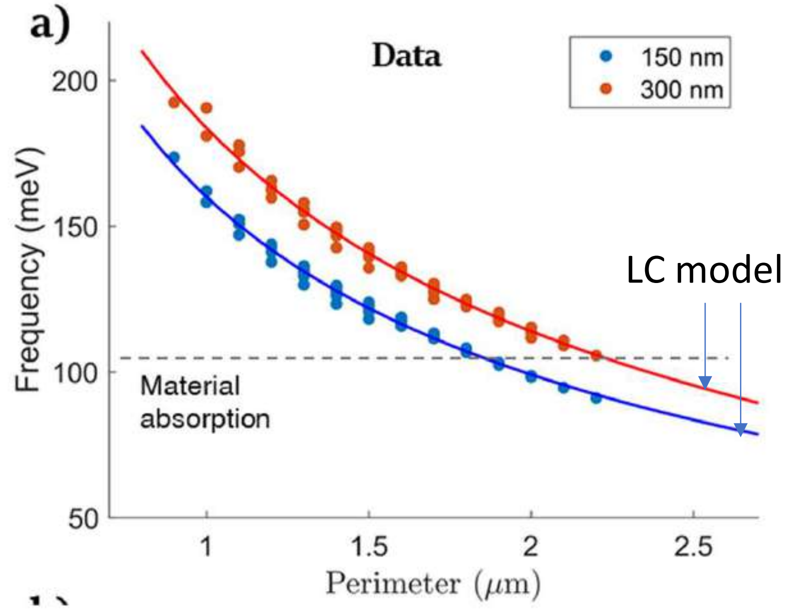


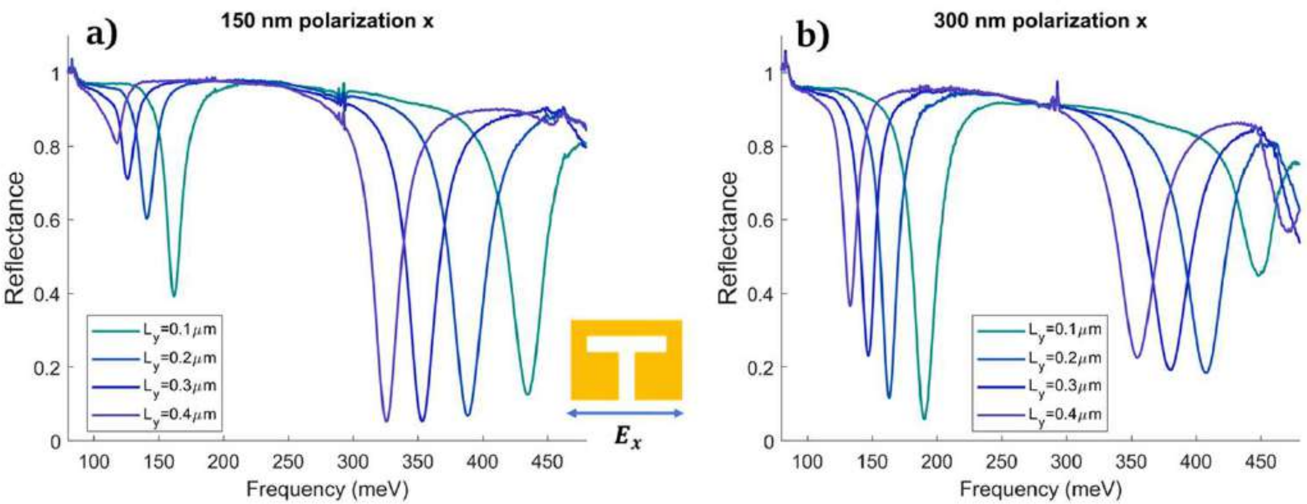
$$\hbar\Omega_{\mathrm{Rabi}} \propto \sqrt{\frac{N_{electrons}}{V_{cavity}}} = const$$ **, but V is much smaller!**

M. Jeannin et al. ACS Photonics **6** (5), 1207-1215 (2019)

Works also for the MIR range (10x shorter wavelengths)

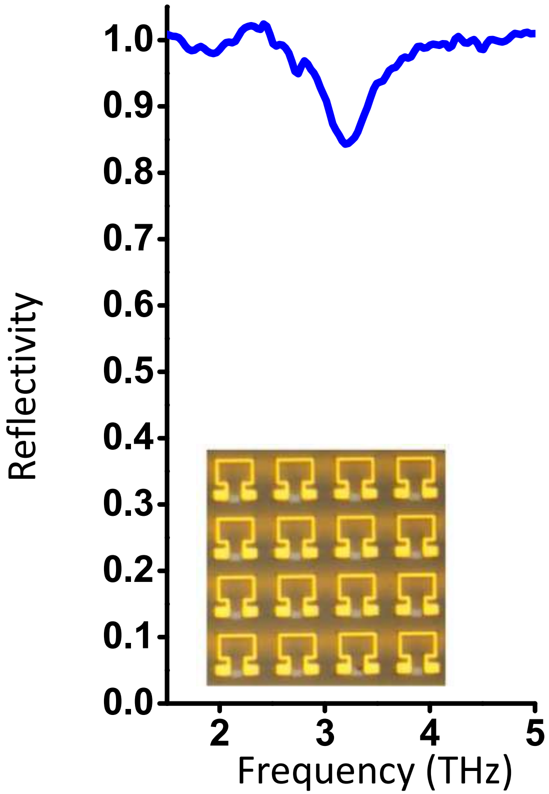


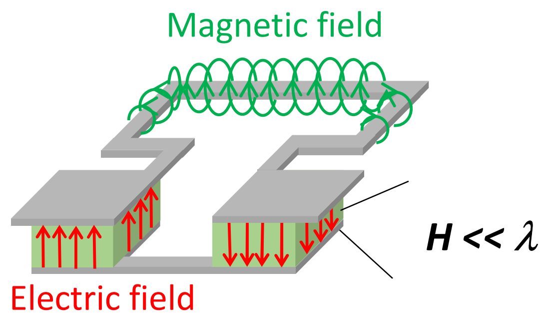




3D Meta-Atoms for High Confinement of Mid-IR Radiation
F. Pisani, et al. ADOM (2025)

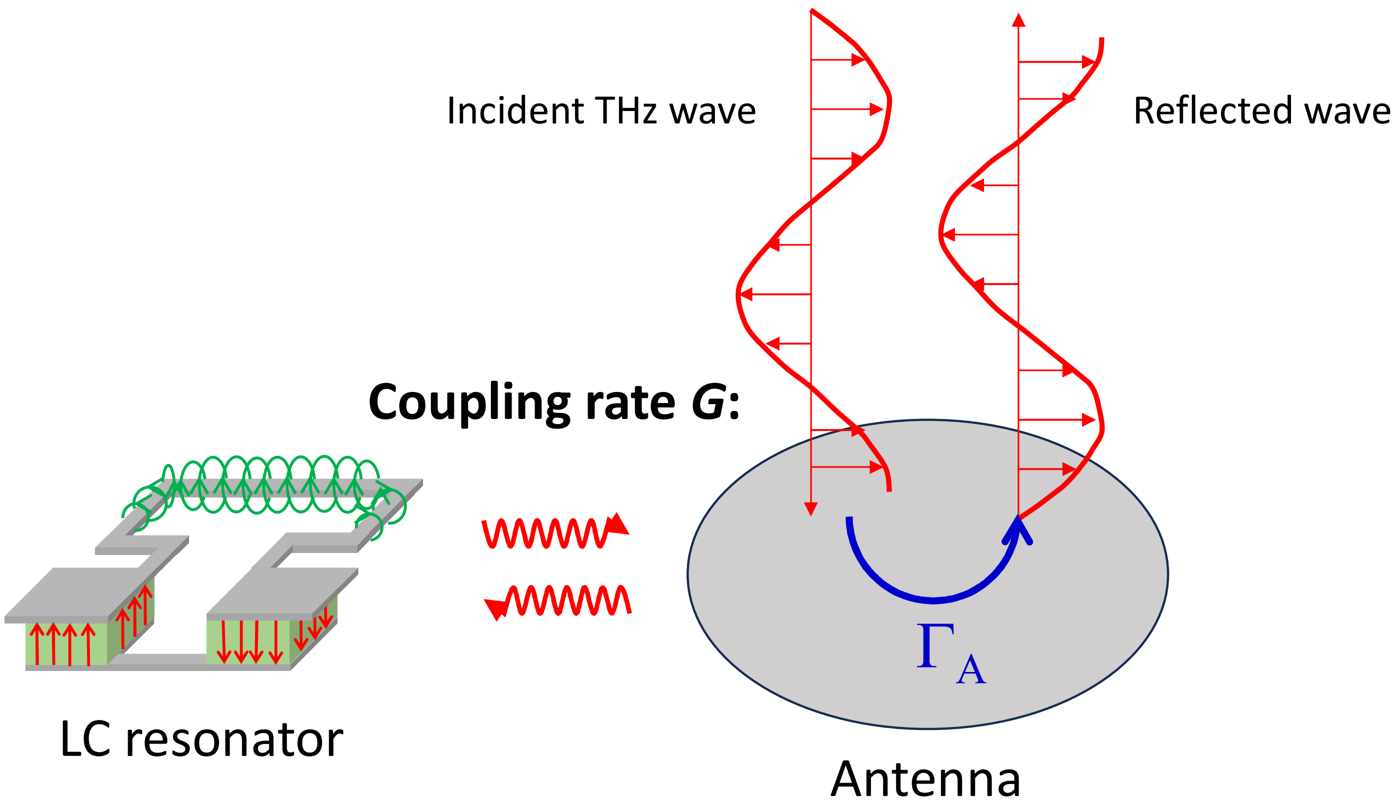
Problem: very low radiation loss…





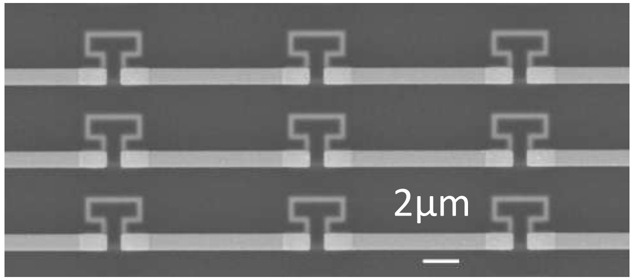
$$\Gamma_{rad} \sim \frac{cH}{\Sigma}$$

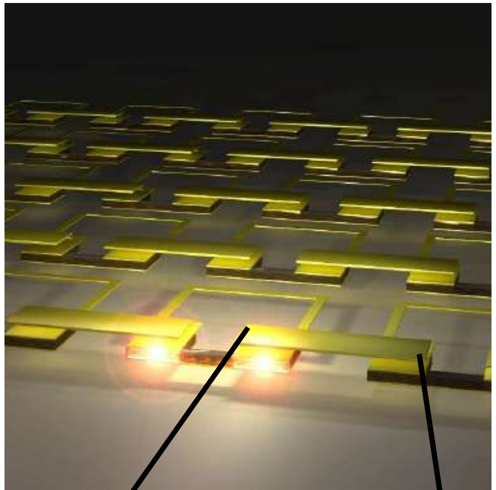
Idea: couple the resonator with an element that has high radiation loss

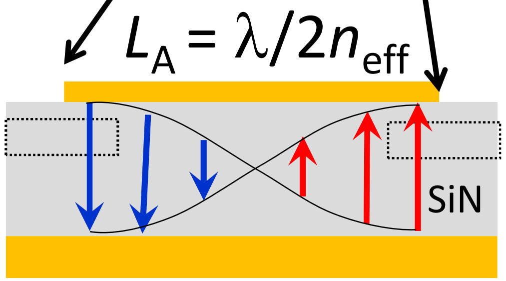


Side-coupling to wire patch antennas

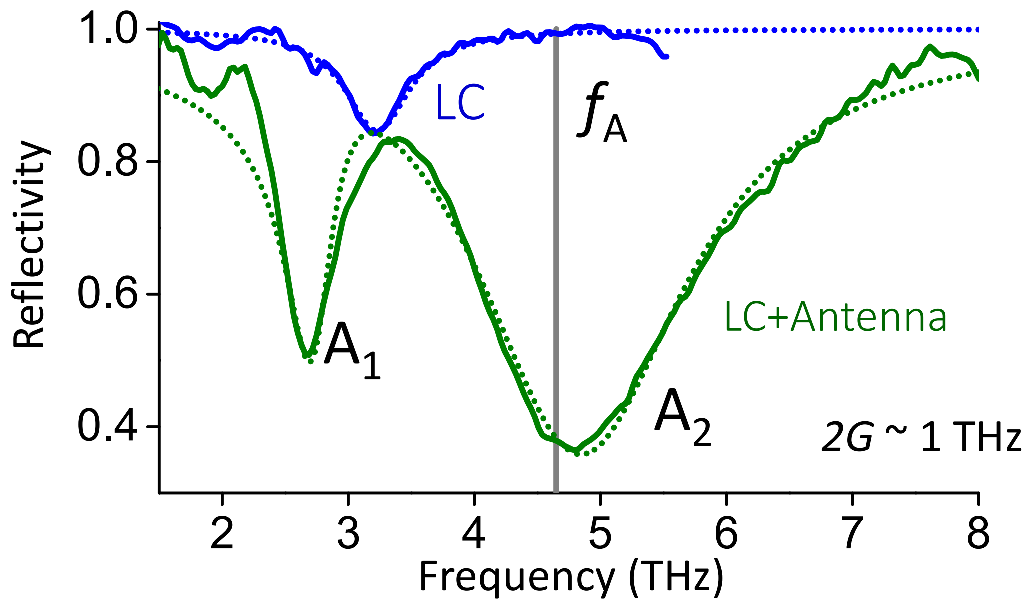
M. Jeannin et al. Nano Lett. **20**(6), 4430−4436 (2020)



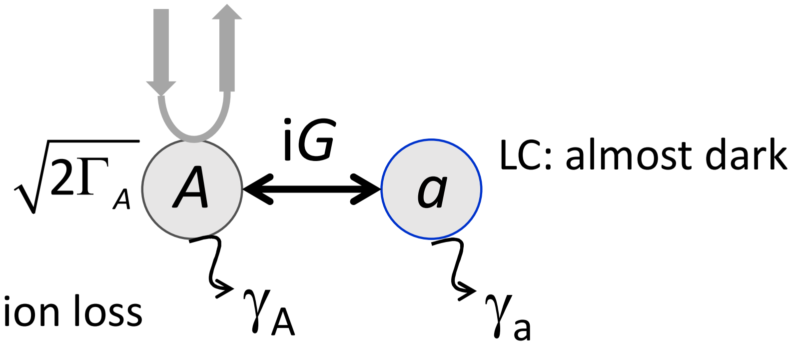




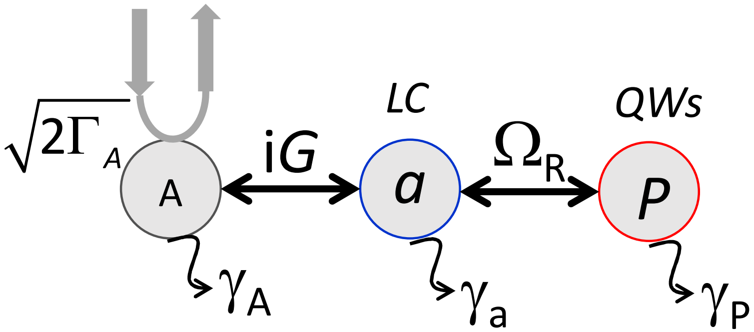
“Wire” patch antenna

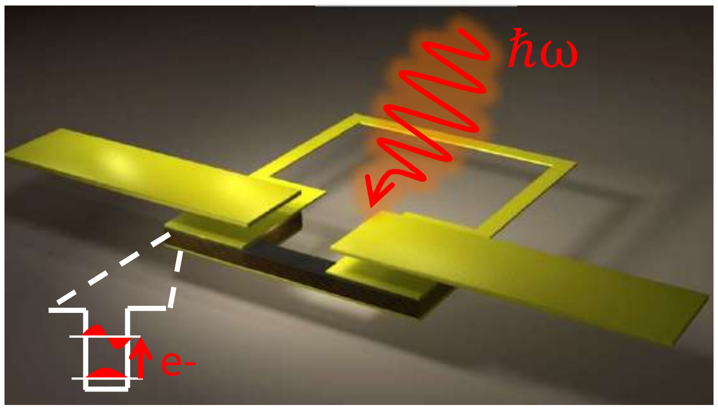


Coupled-Mode theory diagram:

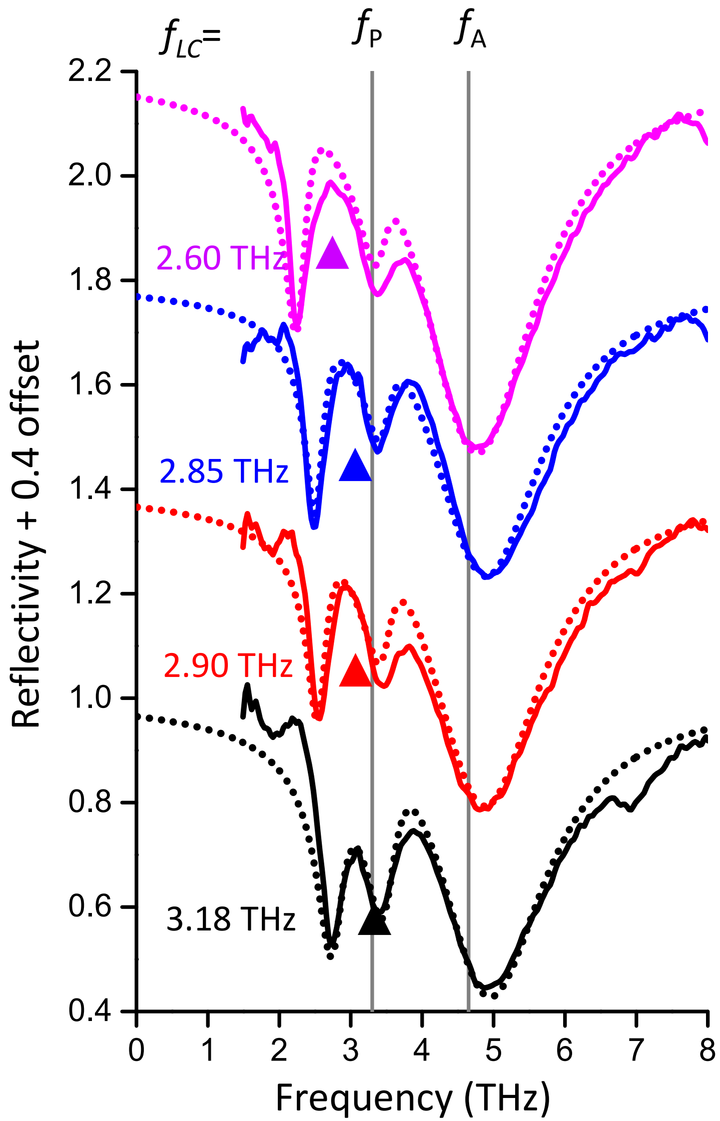


Strong coupling with QW: the mode volume is preserved





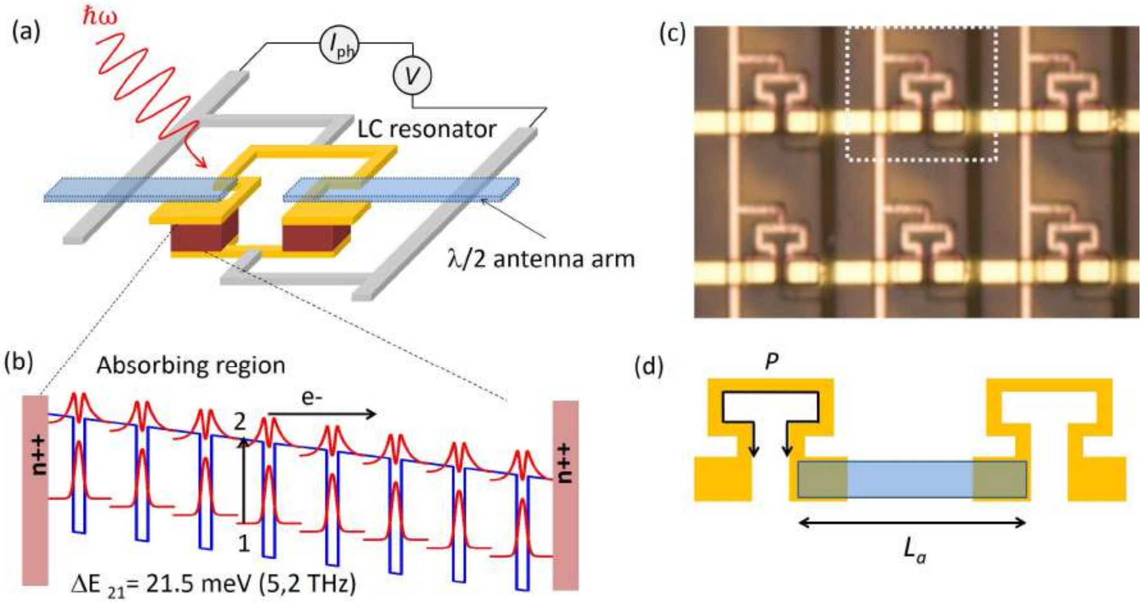
M. Jeannin et al. Nano Lett. **20**(6), 4430−4436 (2020)

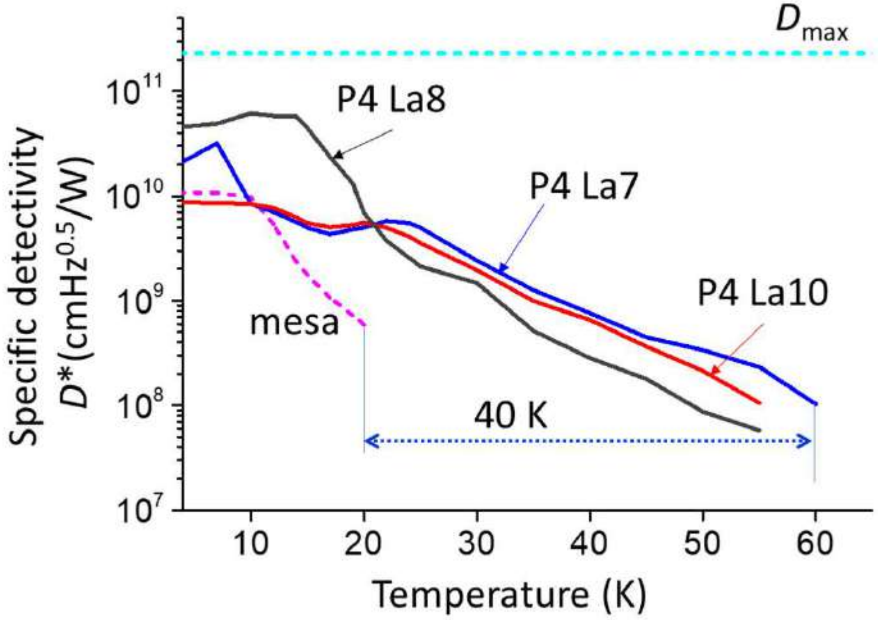


The same Ω_R is obtained as in the case without antenna:

Sub-wavelenght confinement is preserved! ☺

Application for THz detection

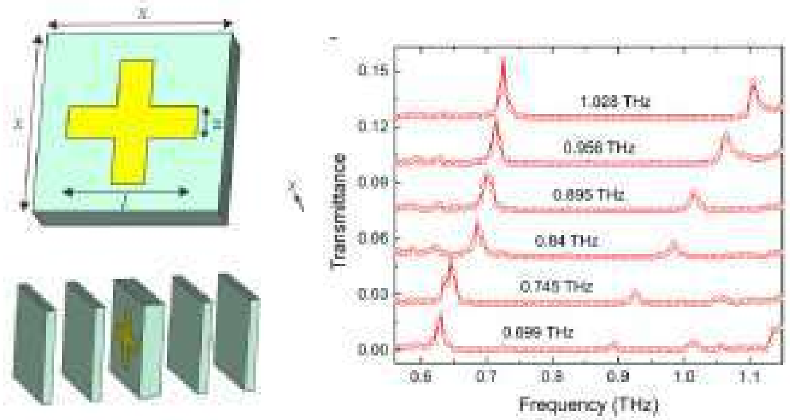




Jeannin et al., Appl. Phys. Lett. **117**, 251102 (2020)

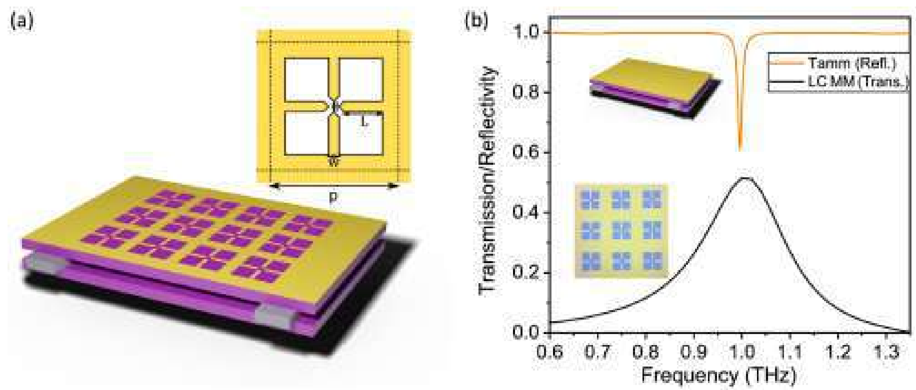
Recent developments on coupled THz resonators

- Coupling between SRRs and Bragg Cavities
  Hartmut Roskos, Goethe-University Frankfurt am Main



F. Meng, et al. ,” Opt. Express 29, 42420–42434 (2021)

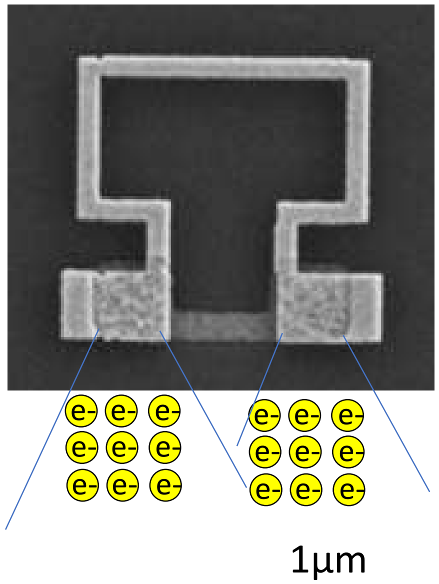
- Low mode volume and High-Q factors
  Juliette Mangeney , LPENS (Paris)

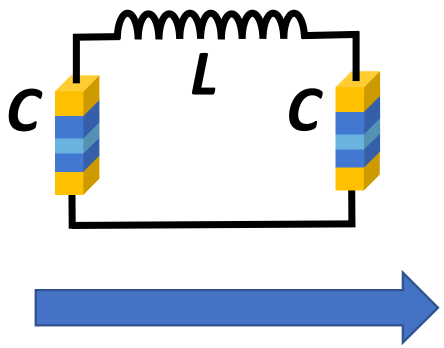


Messelot, et al. Photon. Res. 11, 1203-1216 (2023)

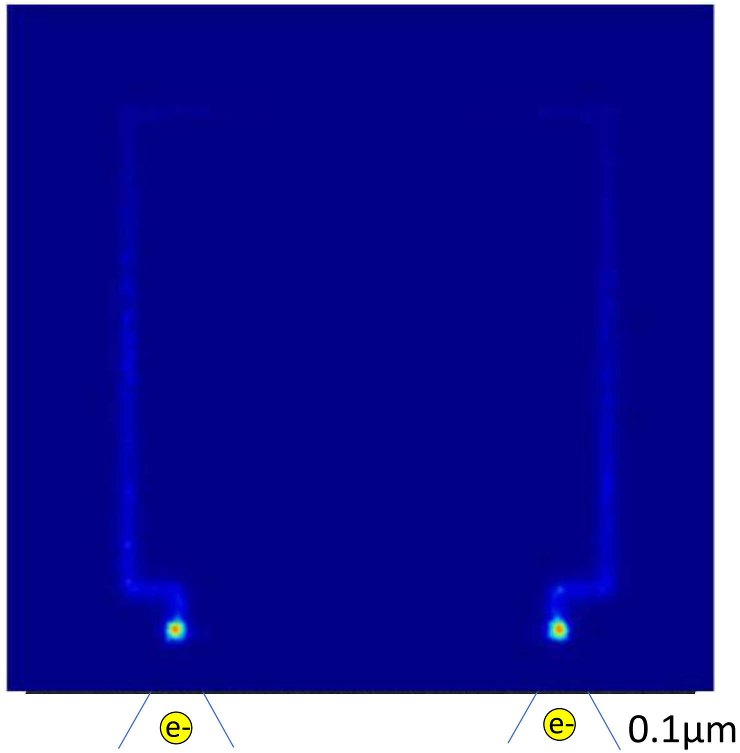
Towards quantum effects in THz metamaterials

Ultra-strong light-matter coupling with THz meta-atoms: single electron limit?





$$\omega_{LC} = \frac{1}{\sqrt{LC}}$$

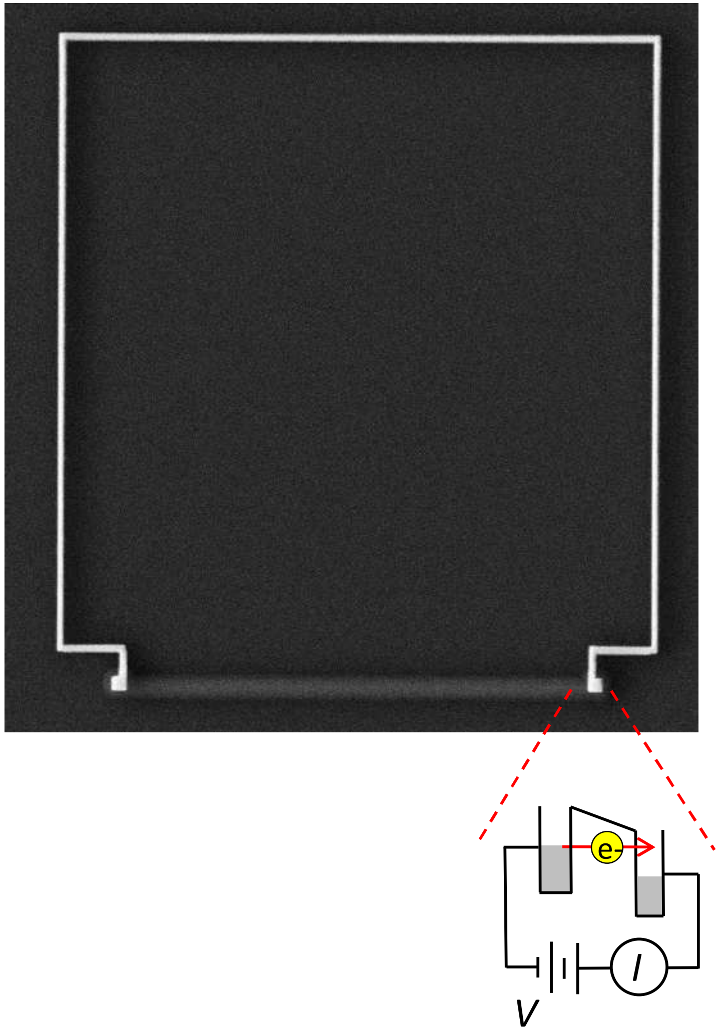


$$\frac{\Omega_R^2}{\omega_{12}^2} \approx \frac{e^2/2C}{\hbar\omega_{LC}} = \rho_0$$

Todorov, PRX **4**, 041031 (2014)

Keller et al. Nano Lett. **17** (2017)

Single electron limit with a metamaterial coupled tunnel junction



$$\frac{\Omega_R^2}{\omega_{12}^2} \approx \frac{e^2/2C}{\hbar\omega_{LC}}$$

$e^2/2C$ → Electrostatic energy of a single electron

$\hbar\omega_{LC}$ → Oscillation quantum of the circuit

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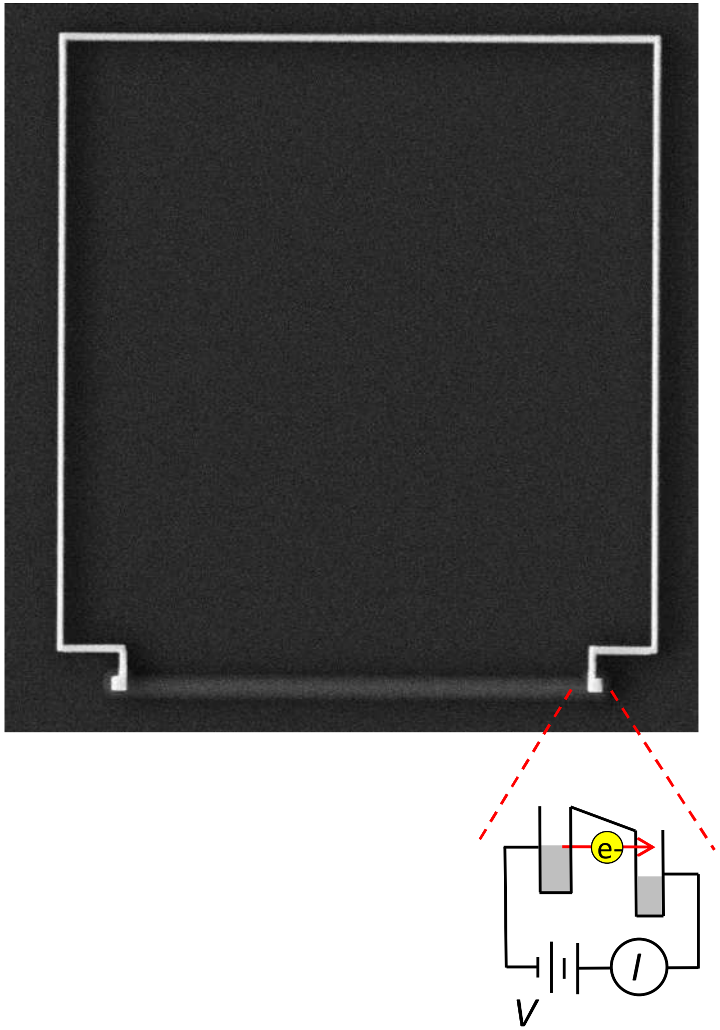
Effect of the Electromagnetic Environment on the Coulomb Blockade in Ultrasmall Tunnel Junctions

M. H. Devoret,[1] D. Esteve,[1] H. Grabert,[2] G.-L. Ingold,[2] H. Pothier,[1] and C. Urbina[1]
[1]*Service de Physique du Solide et de Résonance Magnétique, Centre d'Études Nucléaires de Saclay, 91191 Gif-sur-Yvette, France*
[2]*Fachbereich Physik, Universität–Gesamthochschule Essen, 4300 Essen, Federal Republic of Germany*
(Received 4 December 1989)

Quantum Fluctuations of the LC resonator charge: $\Delta Q^2 = C\frac{\hbar\omega_{LC}}{2}$

If $\Delta Q < e$ the conductance is blocked!

Single electron limit with a metamaterial coupled tunnel junction



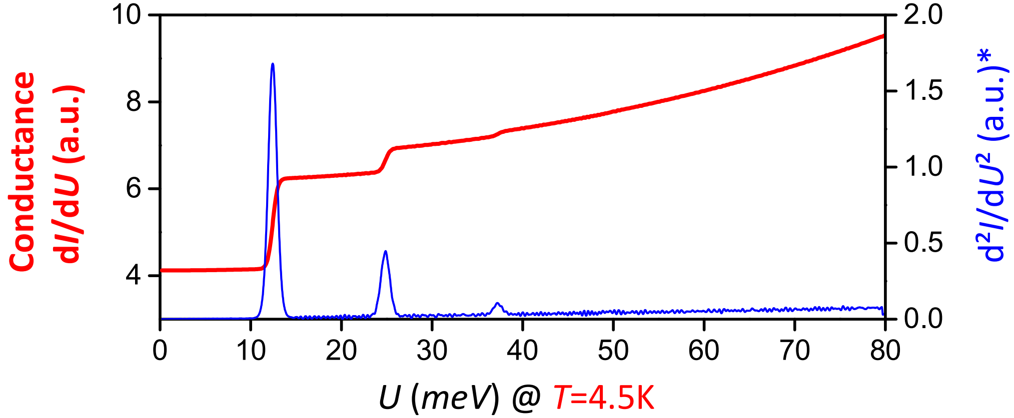
$$\frac{\Omega_R^2}{\omega_{12}^2} \approx \frac{e^2/2C}{\hbar\omega_{LC}}$$

Electrostatic energy of a single electron

Oscillation quantum of the circuit

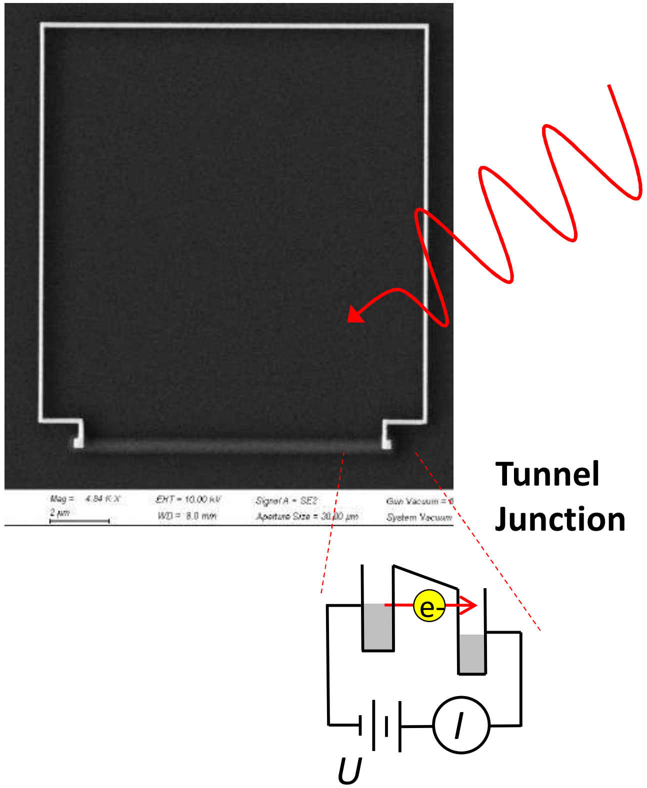
The DC conductance is sensitive
to the vacuum fluctuations of the circuit

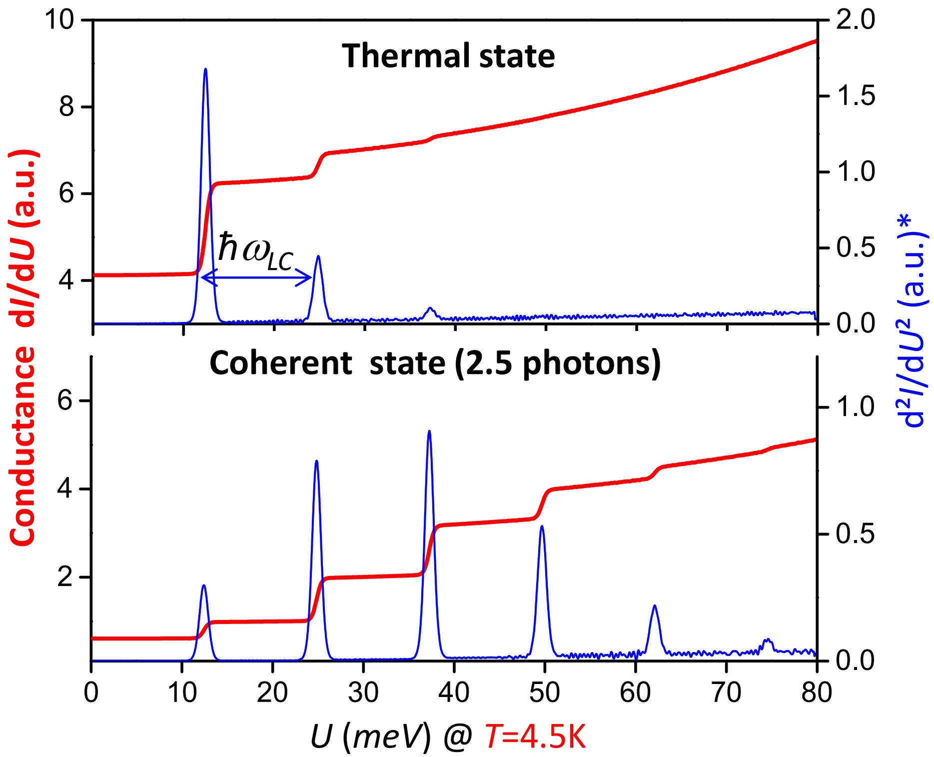
Dynamical Coulomb blockade



Single electron limit with a metamaterial coupled tunnel junction

Read-out of the quantum state of incident THz photons



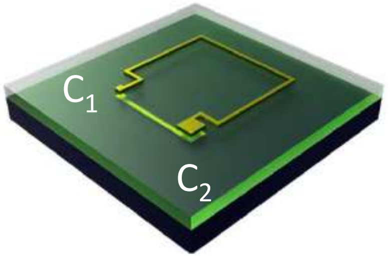


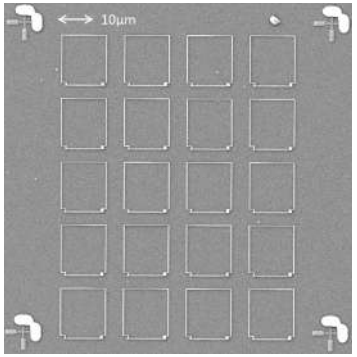
J.-R. Souquet et al., Nat. Comm. **5**, 5562 (2014)
U. Iqbal, C. Mora, and Y. Todorov, Phys. Rev. Research 6, 033097 (2024)

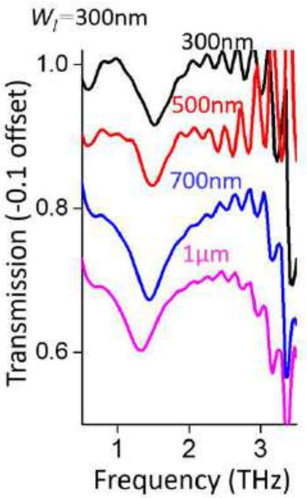
THz meta-atoms in nanoscale capacitors

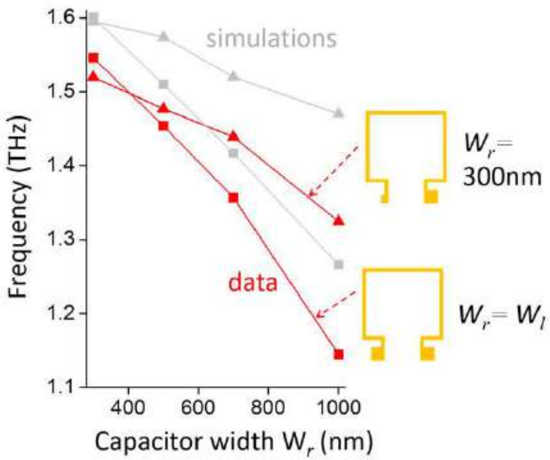
Iqbal et al., Optics Express **34**, pp. 30442-30454 (2026)

Rediscovering the composition law $C_{eq} = \dfrac{C_1 C_2}{C_1 + C_2}$

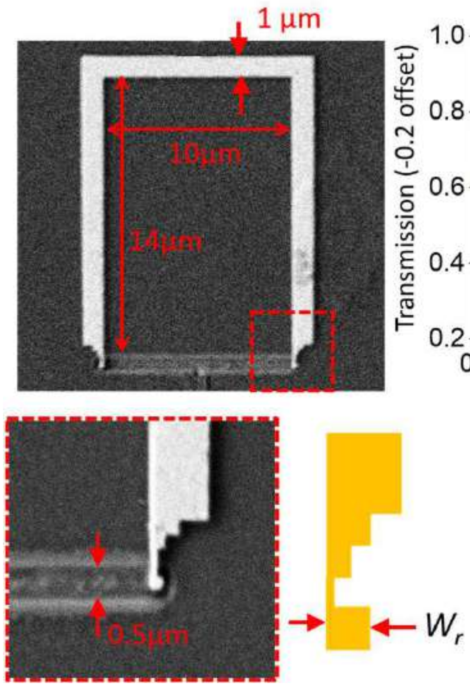


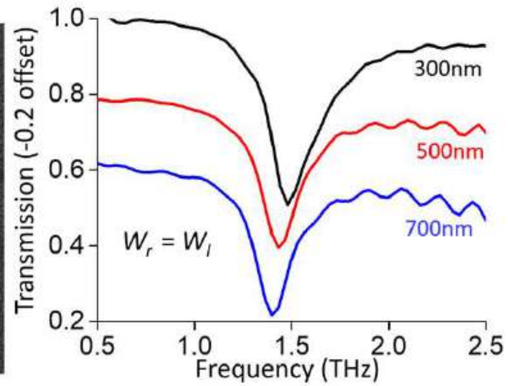




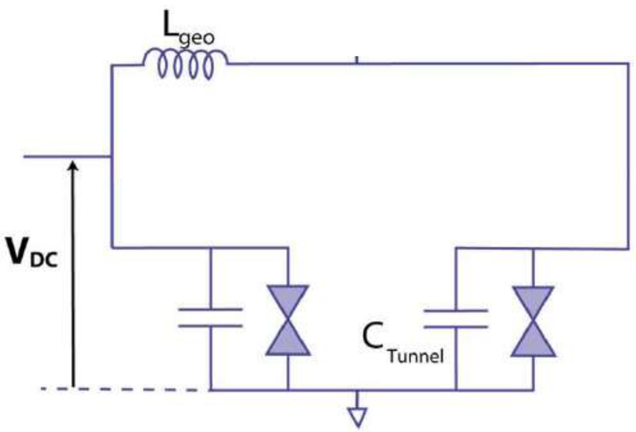


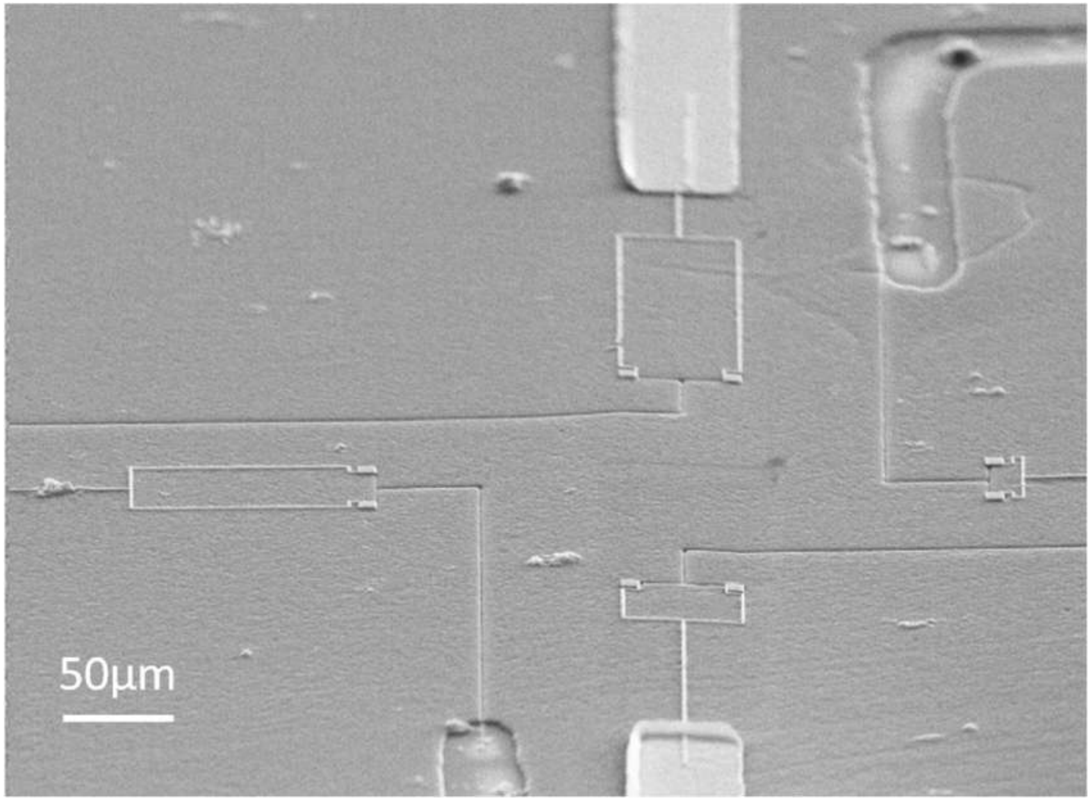
Optimizing the ohmic loss





Towards experimental realizations… stay tuned!





Thank You ! Questions ?

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L. H. Li, A. G. Davies,
E. H. Linfield

UNIVERSITY OF LEEDS

Hua Li, W. Wan, Z. Zhang

Key Laboratory of
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I. Sagnes

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LABORATOIRE DE PHYSIQUE
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R. Perreti,
IEMN Lille,
France

D. But, W. Knap, et al.
Centera,
Warsaw

B. Fix and
P. Bouchon

ONERA
THE FRENCH AEROSPACE LAB

cmQED team

C. Feuillet-Palma,
A. Jouan

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