Metamaterials for THz detection

Carlo Sirtori

Y. Todorov, D. Palaferri, C. Belacel, A. Vasanelli, S. Barbieri, D. Gacemi, I. Favero

Laboratoire Matériaux et Phénomènes Quantiques, Université Paris Diderot – CNRS UMR 7162, 75205 Paris Cedex 13, France

New Frontiers in 2D materials: Approaches & Applications

15-20 January 2017, Villard-de-Lans, FRANCE

ADEQUATE

Collaborators

Epitaxial Growth

UNIVERSITY OF LEEDS

L. H. Li, A. G. Davies,
E. H. Linfield (THz and Mid-IR QWIPs)

School of Electronic and Electrical Engineering, University of Leeds,
Leeds LS2 9JT, United Kingdom

G. Biasiol (Mid-IR QWIPs)

IOM CNR, Laboratorio TASC, Area Science Park,
I-34149 Trieste, Italy

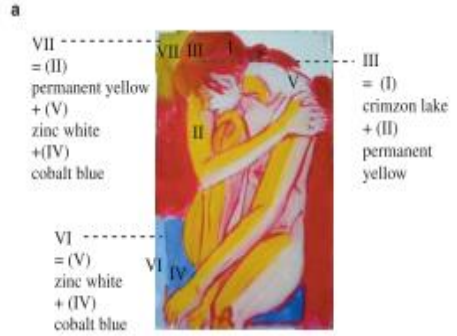
THz applications

- **Terahertz : 1 – 5 THz 300 – 30µm**

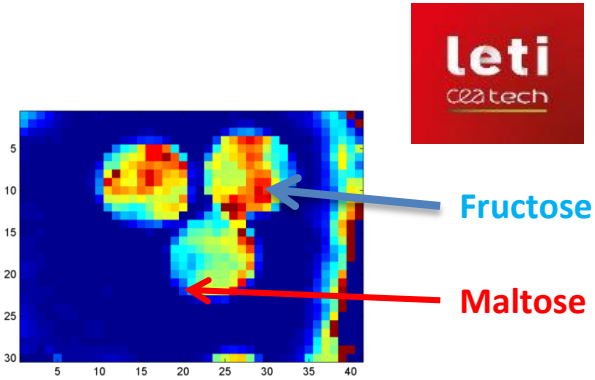
Imaging (cw sources, incoherent detection)

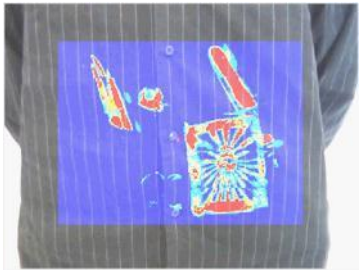
focal planar arrays in conjunction with cw sources

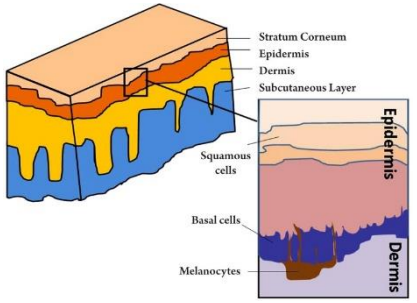
- *Material inspection*
- *Security*
- *Analytical imaging (Food)*
- *Microscopy*
- *Medical (tumor detection)*



K. Fukunaga et. al.
*IEICE Electronics Express, **4**, 8, p. 258 (2007)*







Calvin Yu, et al,
Quant Imaging Med Surg. 2012 Mar; 2(1): 33–45.

Photonic detectors in the THz/MiR

- Photonic (energy) detectors have high dark current

→ cryogenic operation

λ=10µm, T ~ 80K

Image: Judson website

THz: λ=100µm, T ~ 4K

QMC Bolometer

Room temperature

Golay cell

- Schotky

Same detectors for the past 30-40 years

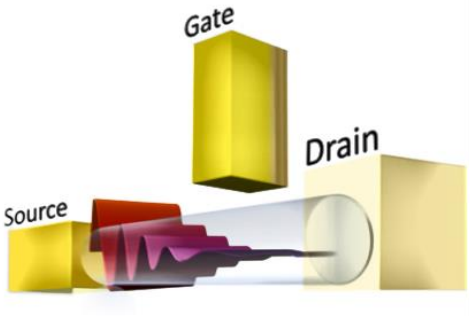
- Good detectors !

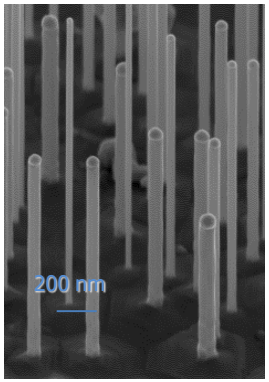
- In continuous evolution

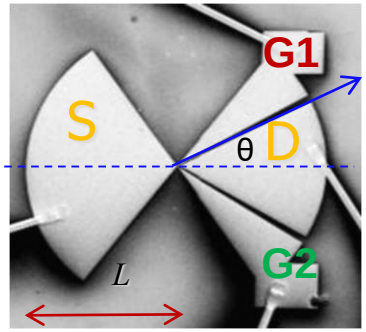
Room Temperature Terahertz Nanodetectors: Nanowires, Graphene, Black Phosphorus

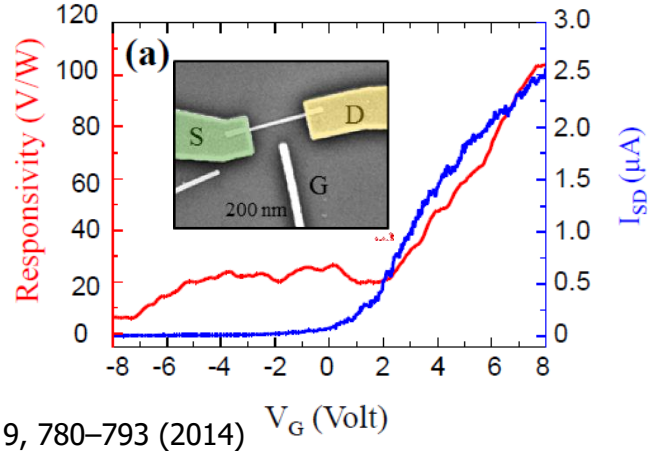
M.S. Vitiello et al. ***Nano Letters*** *2012;* ***APL Materials*** *2015;*

M. Eisele et al. ***Nature Photonics*** *2014*

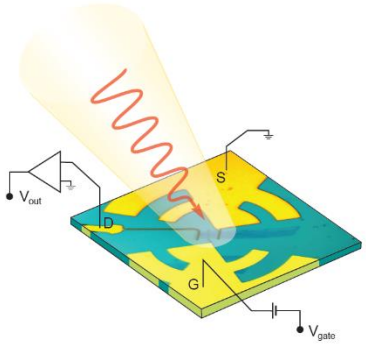


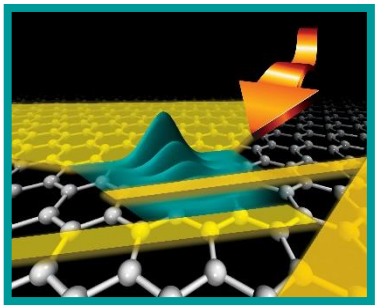


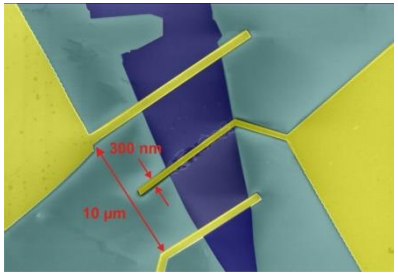


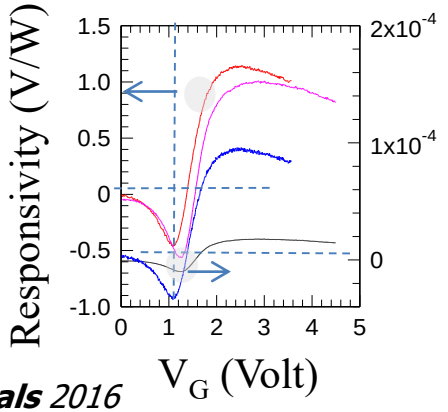


Koppens, Mueller, Avouris, A. C. Ferrari, M. S. Vitiello & M. Polini **, *Nature Nanotechnology*** 9, 780–793 (2014)

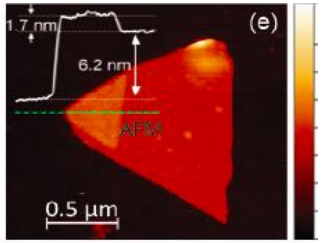


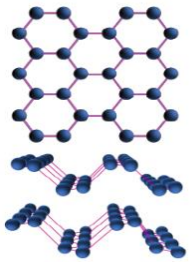


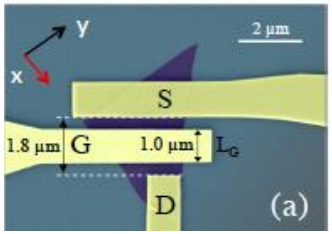


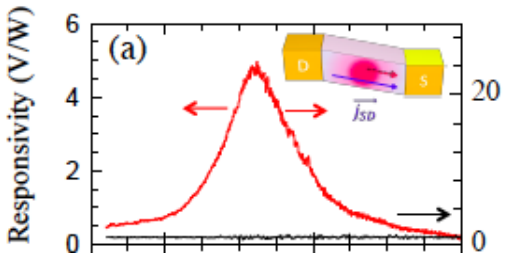


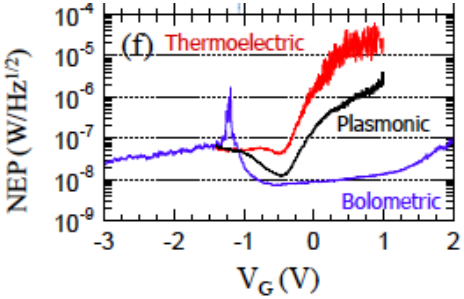
L. Viti et al. ***Advanced Materials*** *2015; Viti et al.* ***Scientific Reports*** *2016;* ***Advanced Materials*** *2016*





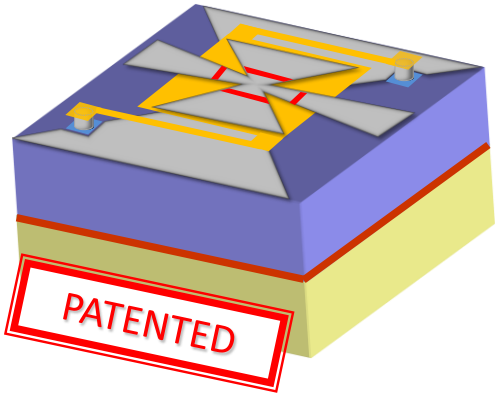




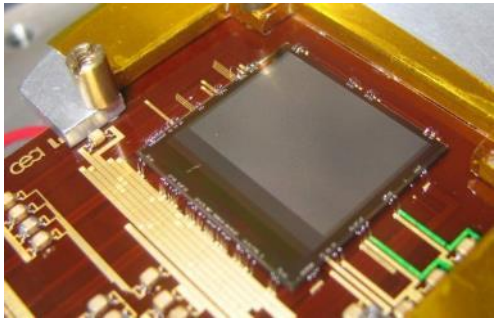


• LETI THz BOLOMETER ARRAY FABRICATION

- FABRICATED ANTENNA-COUPLED M-BOLOMETER FPAS

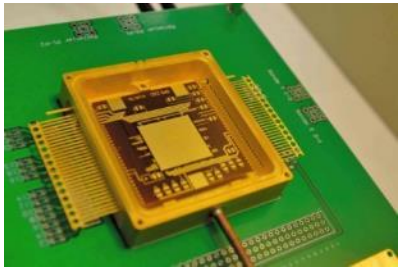


- 320x240 pixel FPA

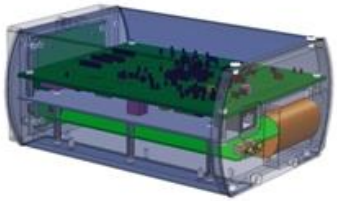


- FPAs integrated in Ethernet video output cameras

Specific vacuum packaging



FPGA front-end electronics



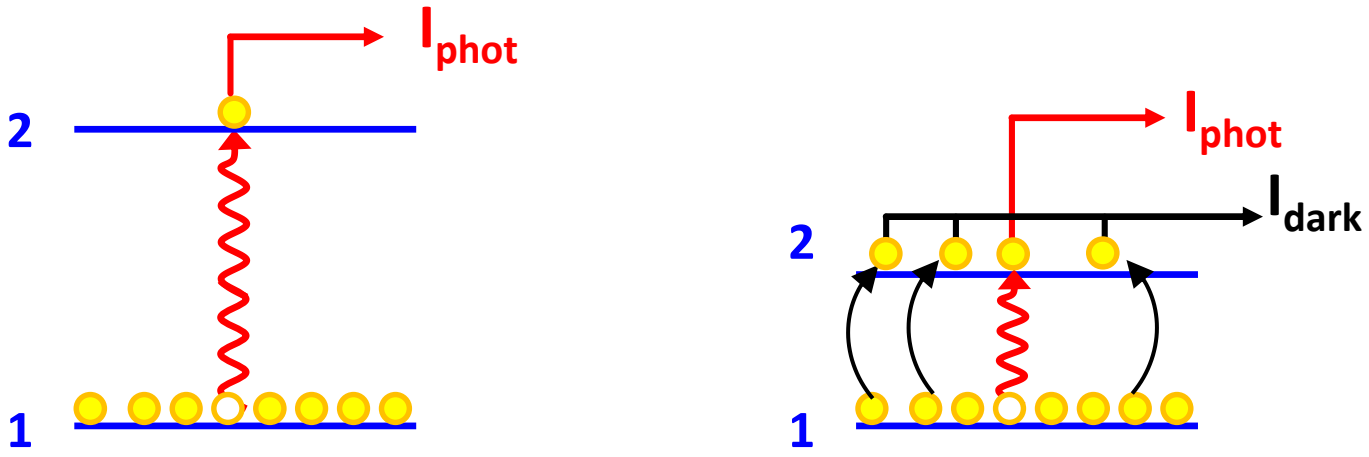
Camera housing

Courtesy of F. Simoens

Photonic detection in the THz → Dark current

The dark current is an activated process:

$$I_{dark} \propto \exp(-E_{act}/kT) \quad \text{where} \quad E_{act} \sim E_{12}$$

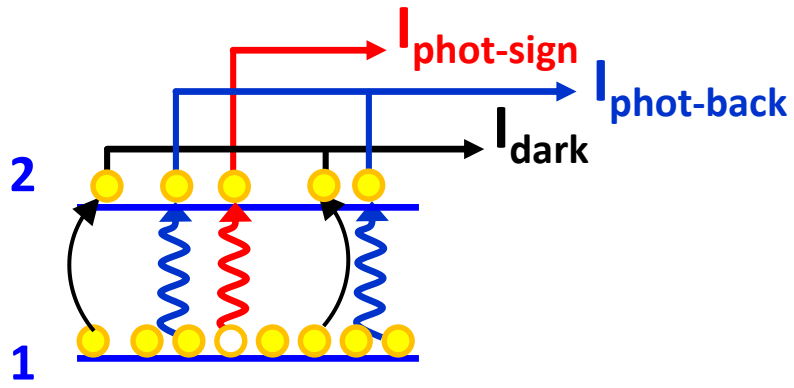


The signal is washed out by the dark current noise → Detector must be cooled!

Background photocurrent

In the far infrared photons are at the equilibrium with the earth temperature
300K Black-Body ~ 300 Wm^{-2}

For cold detectors there is a net flux of photon coming from the background



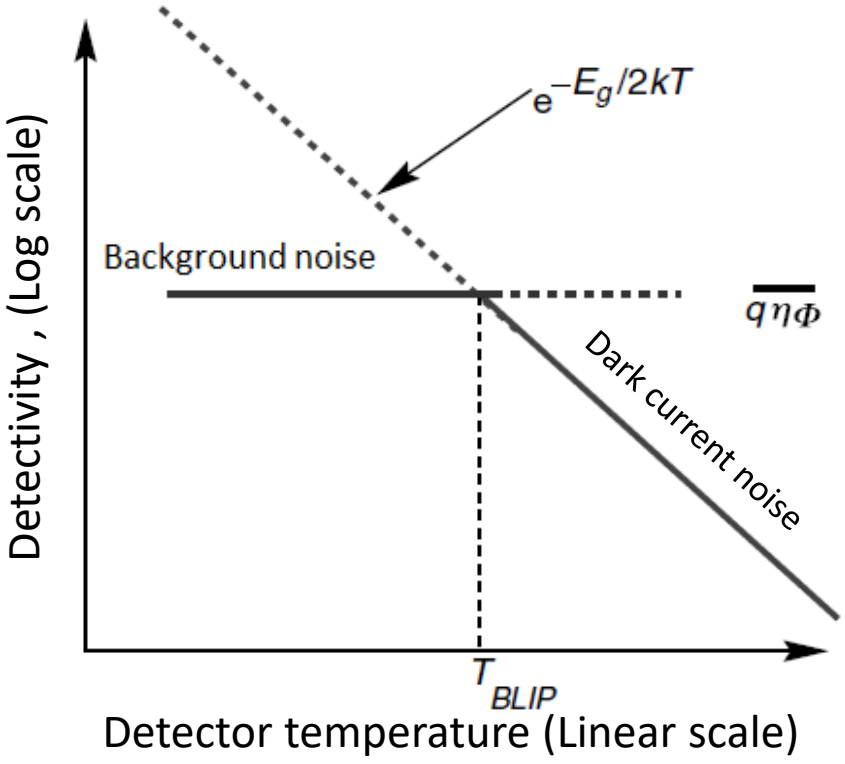
The total current in the detector is $I_{tot} = I_{phot} + I_{phot\text{-}back} + I_{dark}$

$I_{phot\text{-}back}$ contributes to the noise! Current noise $\overline{I_v} = \sqrt{2eg\, I_{tot}\, \Delta\nu}$

Background limited detectivity

$I_{tot} = I_{phot\text{-}sign} + I_{phot\text{-}back} + I_{dark}$

I_{phot}



Background limited Temperature:

$I_{dark}(T_{BLIP}) = I_{phot} = I_{tot} - I_{dark}$

$I_{tot} = 2I_{dark}(T_{BLIP})$

T_{BLIP} is the operating temperature!

$I_{phot\text{-}back} \sim A_{device}$ x photon flux

$I_{dark} \sim A_{device}$ x exp $(-E_{12}/k_BT)$

Figure of merits for detectors

Photoconductor detectors

$$\overline{I_v} = \sqrt{2eg\, I_{tot}\, \Delta\nu}$$

Responsivity

$$R = \frac{I_{phot}}{P_{in}} \quad [\mathrm{A/W}]$$

Noise Equivalent Power

$$NEP = \frac{\text{Current noise}}{\text{Responsivity}} = \frac{\overline{I_v}}{R} \quad [\mathrm{W/(Hz^{1/2})}]$$

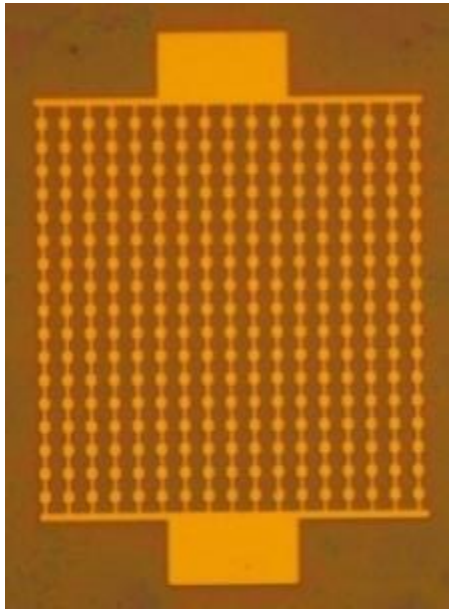
Detectivity

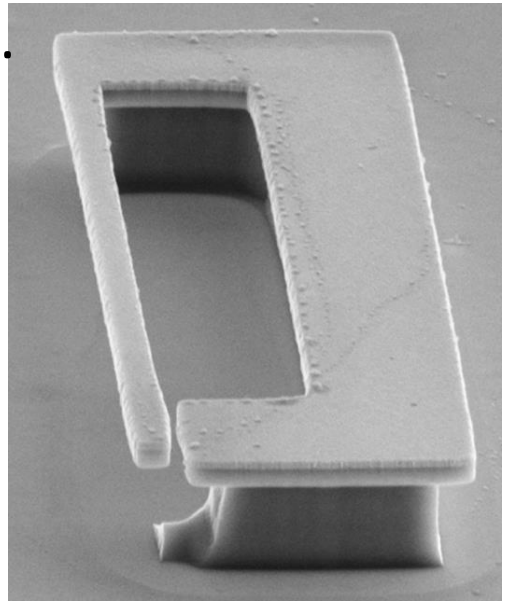
$$D^* = \frac{\sqrt{A\, f}}{\mathrm{NEP}} \quad [\mathrm{cm\ Hz^{1/2}/W}]$$

Outline

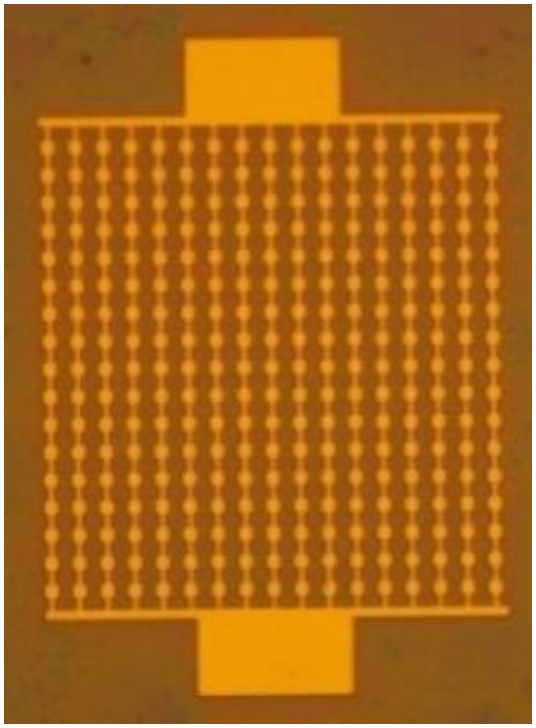
1. Antenna and circuit concepts for Quantum THz detectors

2. Optomechanical THz detection using metamaterials

1. 

2. 

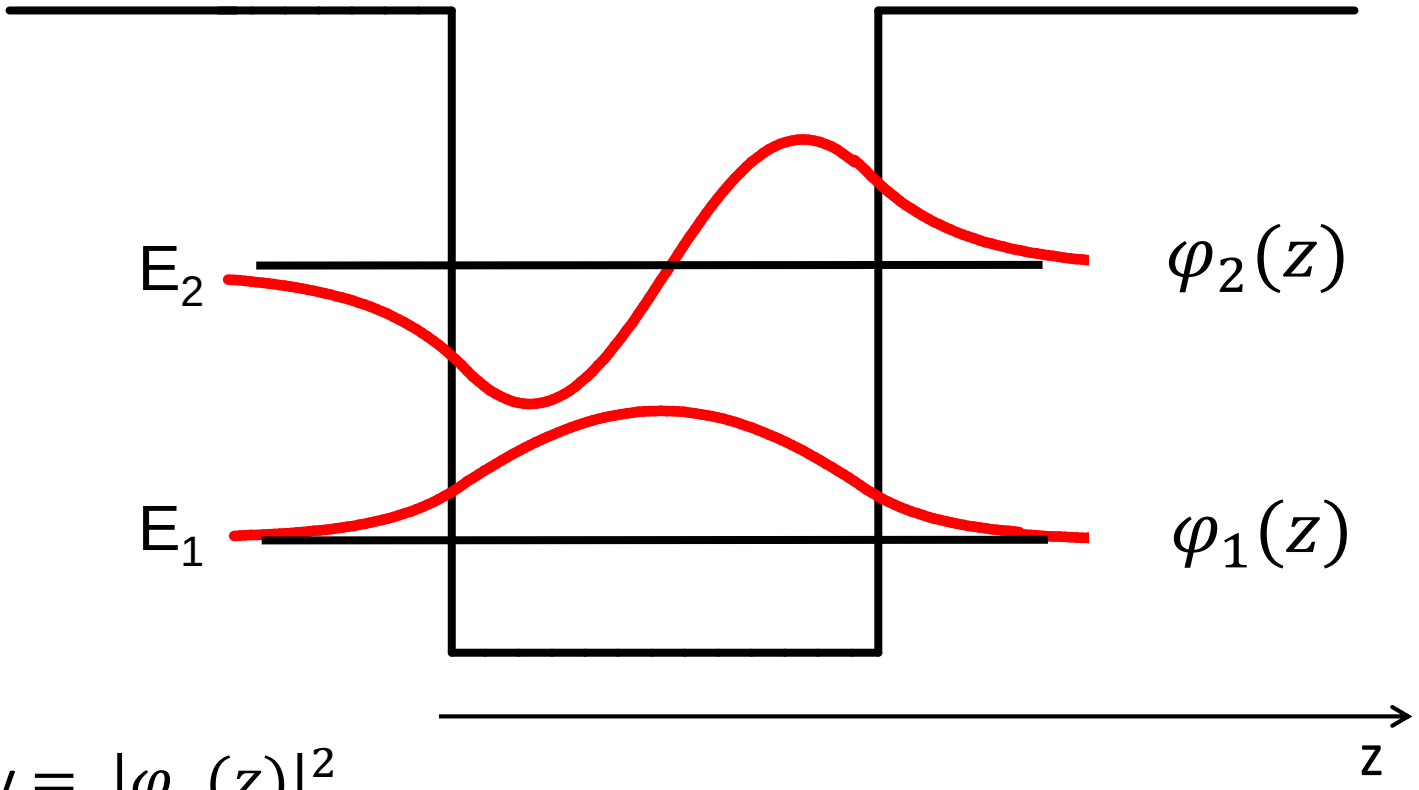
Antenna coupled microcavities for Quantum THz detectors



Quantum well potential

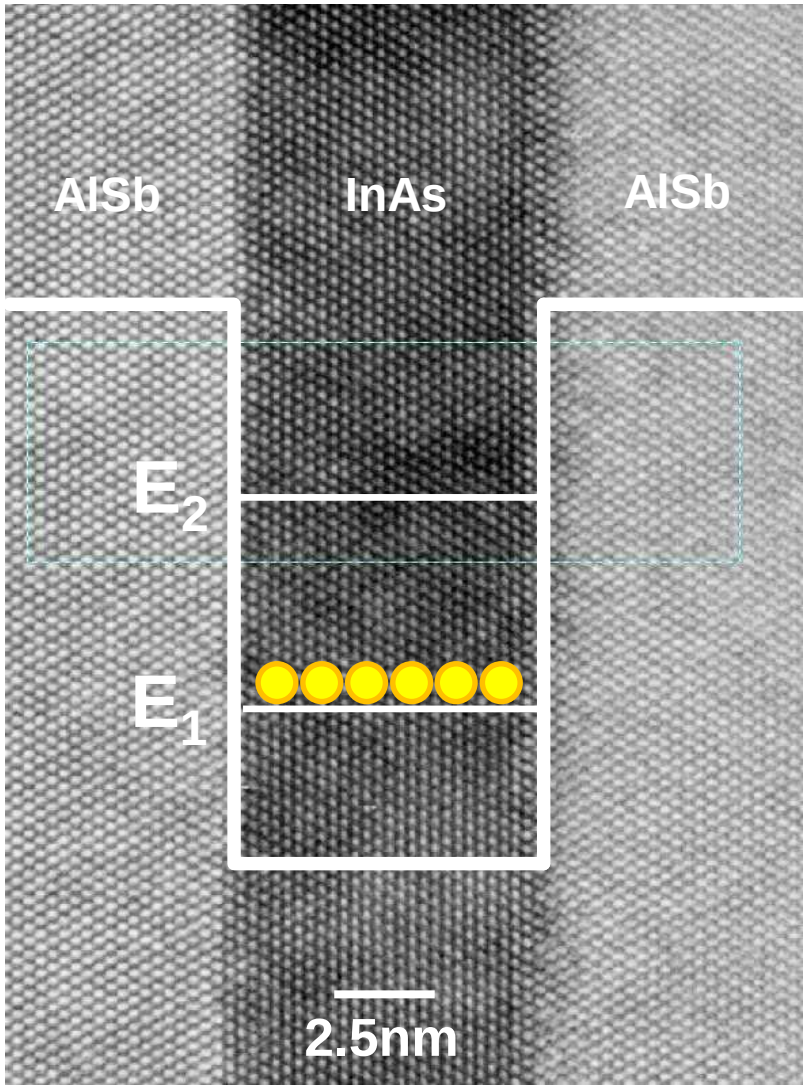
The Schrodinger equation

$$H\,\psi = E\,\psi \quad with \quad H = \frac{p^2}{2m^*} + V(z)$$



Probability = $|\varphi_n(z)|^2$

Quantum potential in semiconductors

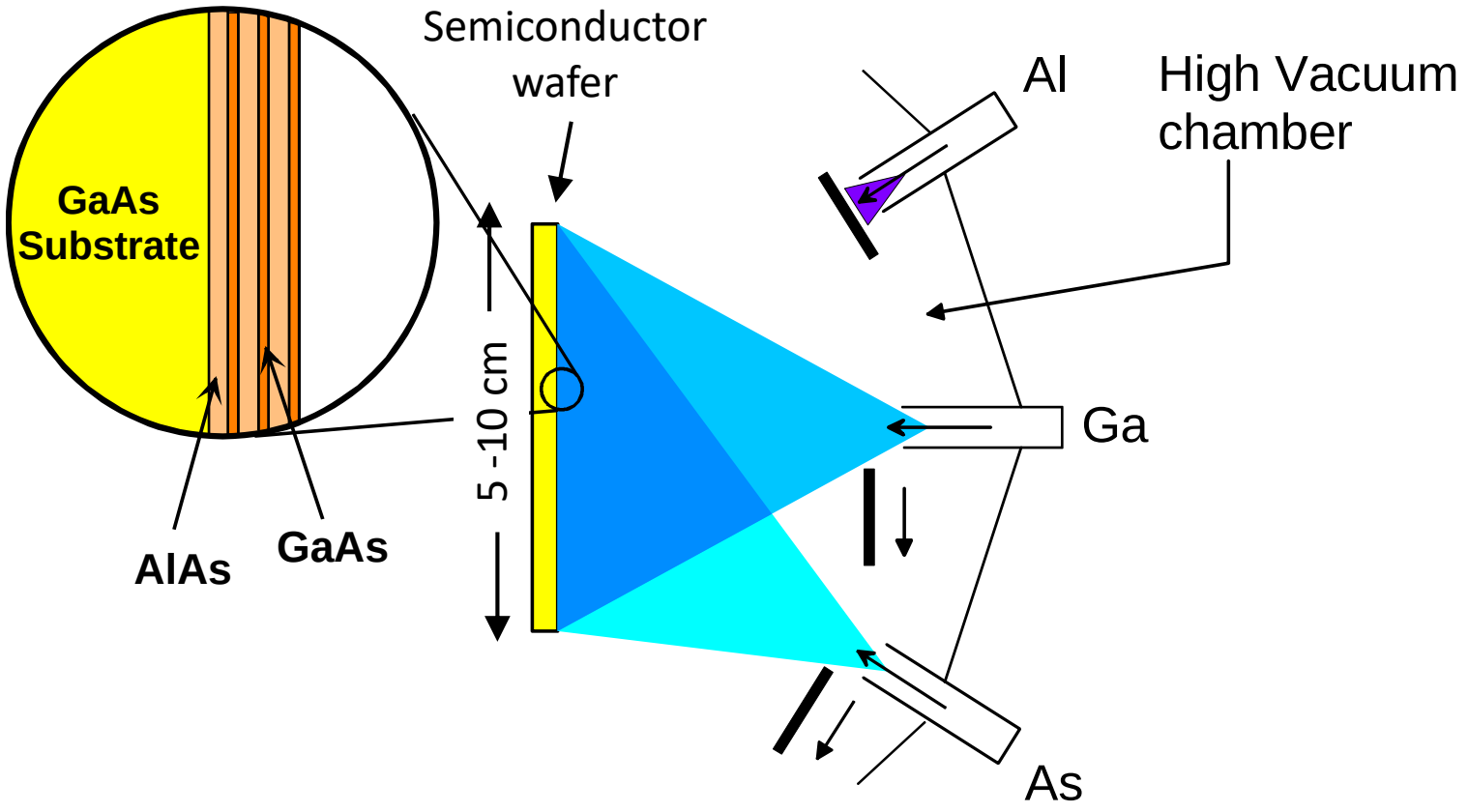


Epitaxially grown material with very abrupt interfaces

The quantum well is the elementary constituent of more complex potentials

Molecular beam epitaxy

Different semiconductors may have the same lattice constant and can be grown into a single crystal structure

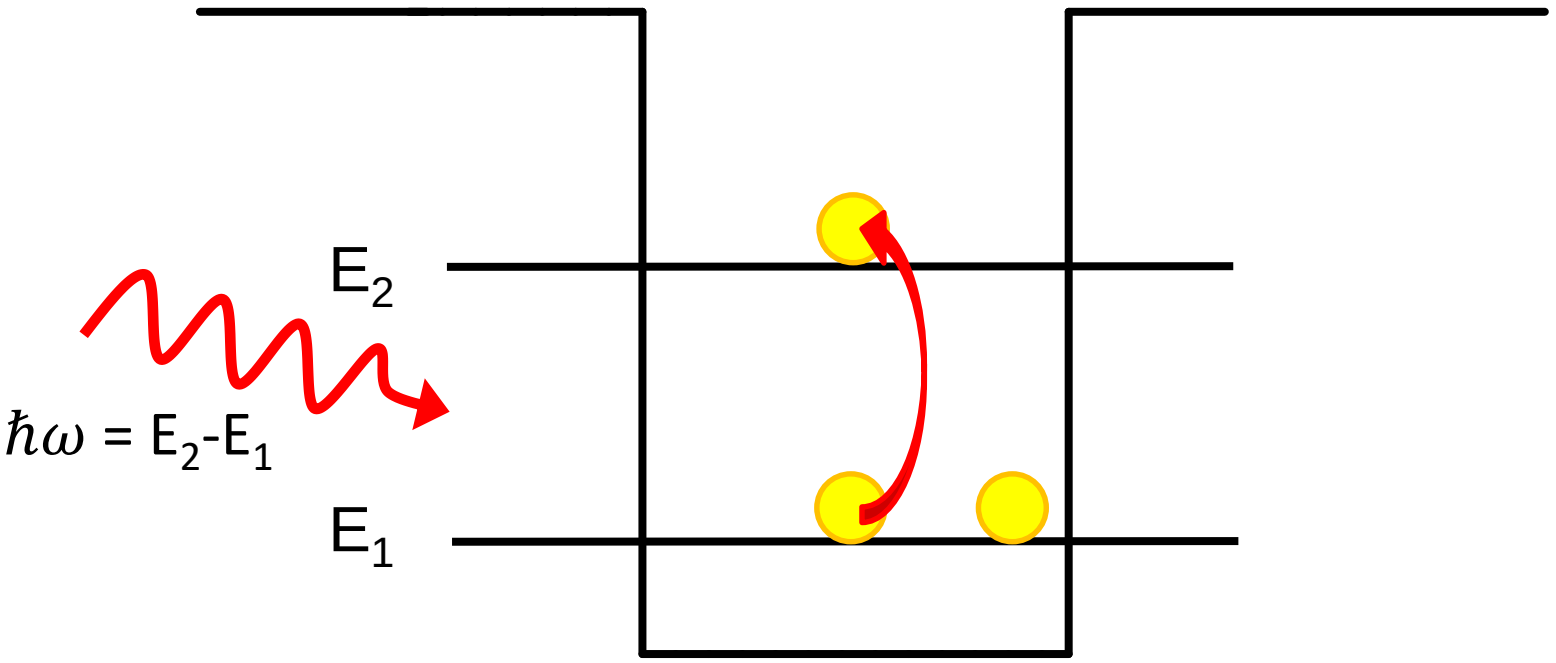


Deposition of atomic layer after atomic layer

Light-matter interaction in quantum quantum wells

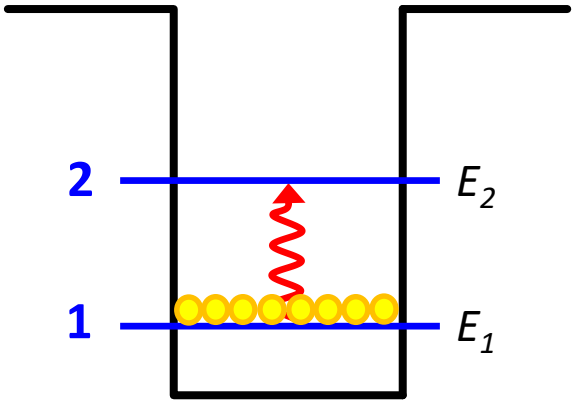
Light-matter interaction

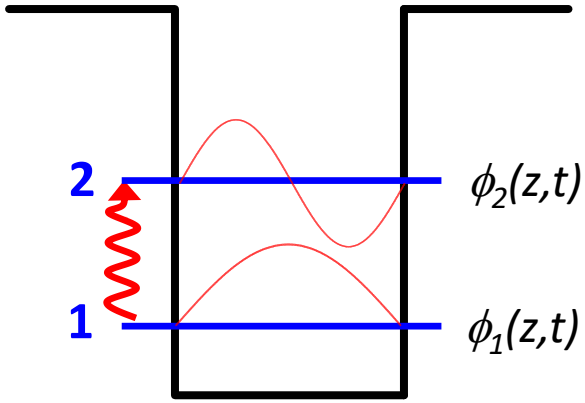
Energy exchange between a photon and the quantum structure



$E_2 - E_1 < 1eV$ → The transitions are typically in the infrared

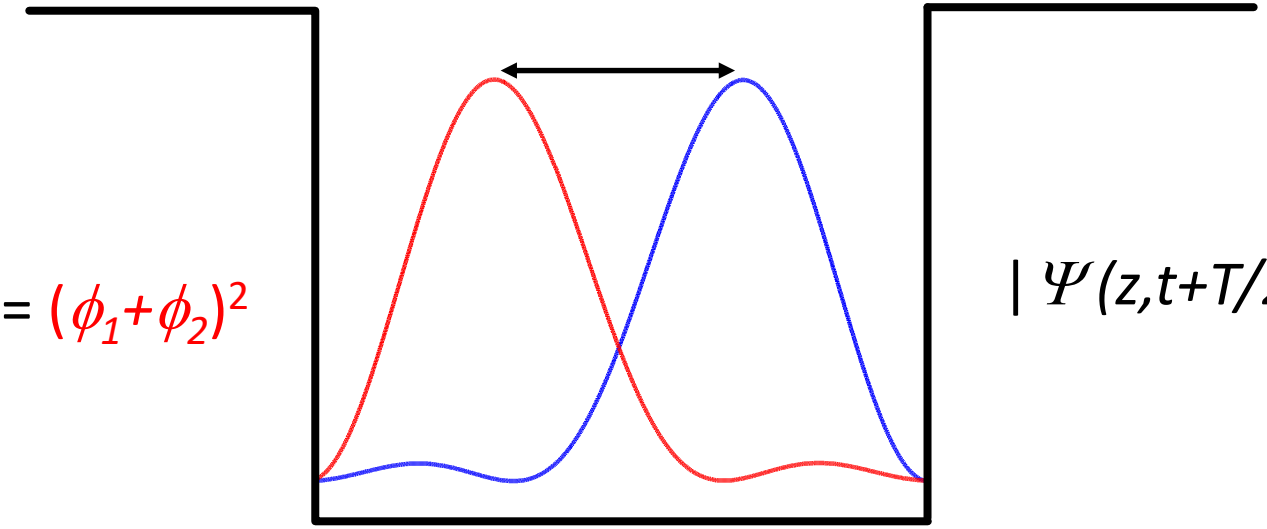
Intersubband transitions





$$|\Psi(z,t)|^2 = |\phi_1(z,t) + \phi_2(z,t)|^2$$

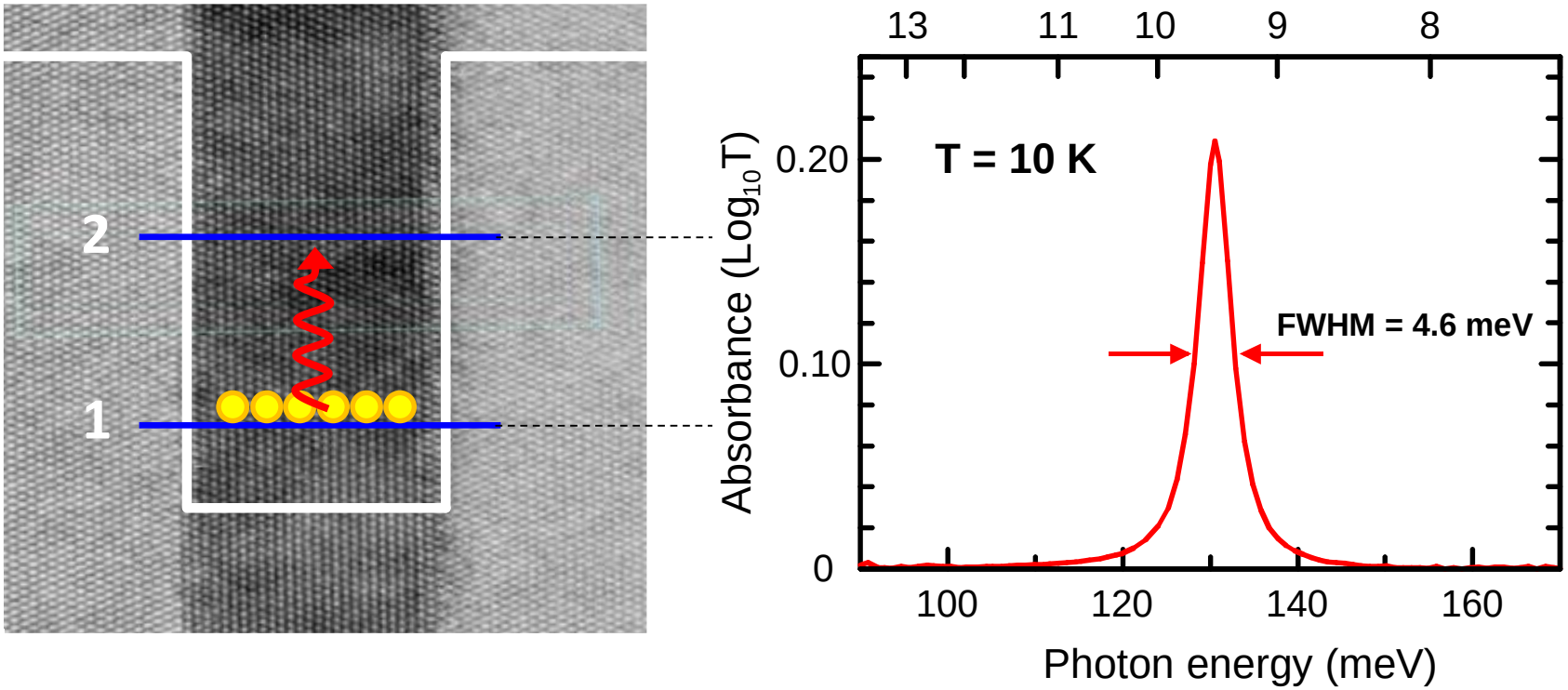
$|\Psi(z,t)|^2 = (\phi_1+\phi_2)^2$



$|\Psi(z,t+T/2)|^2 = (\phi_1-\phi_2)^2$

Intersubband transitions (absorption)

The absorption of a photon is related only to the energy difference between the subbands et does not depends on $k_{//}$



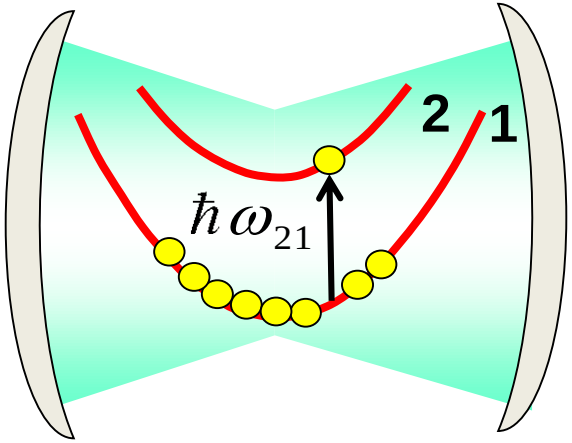
$$E_{n,k} - E_{m,k} = \Delta E_{nm} \quad \forall k$$

Absorption peaks like in 3D confined potentials: atoms

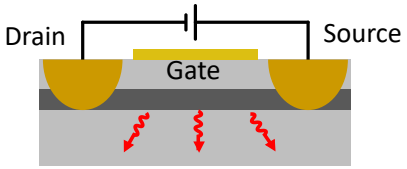
Many-body quantum optics

Fundamental investigations

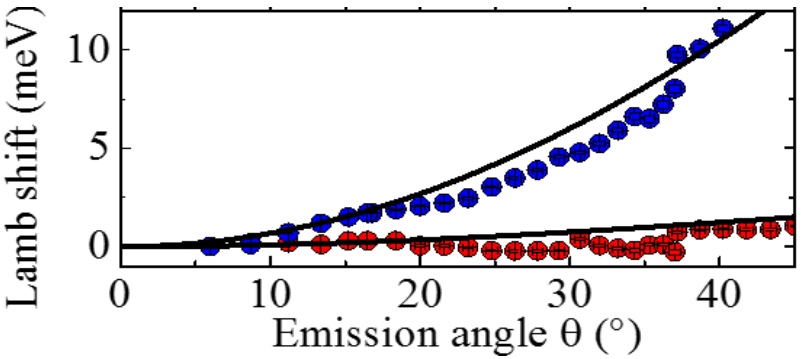
Ultra strong coupling



Supperadiance



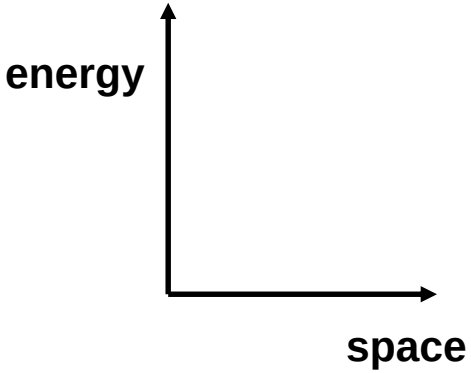
Cooperative Lamb Shift

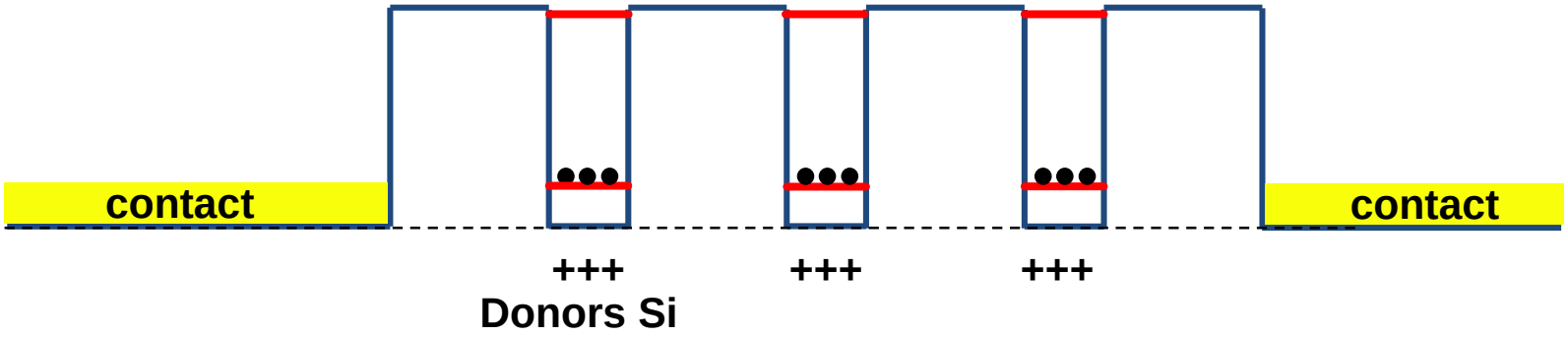


Quantum well infrared photodetector

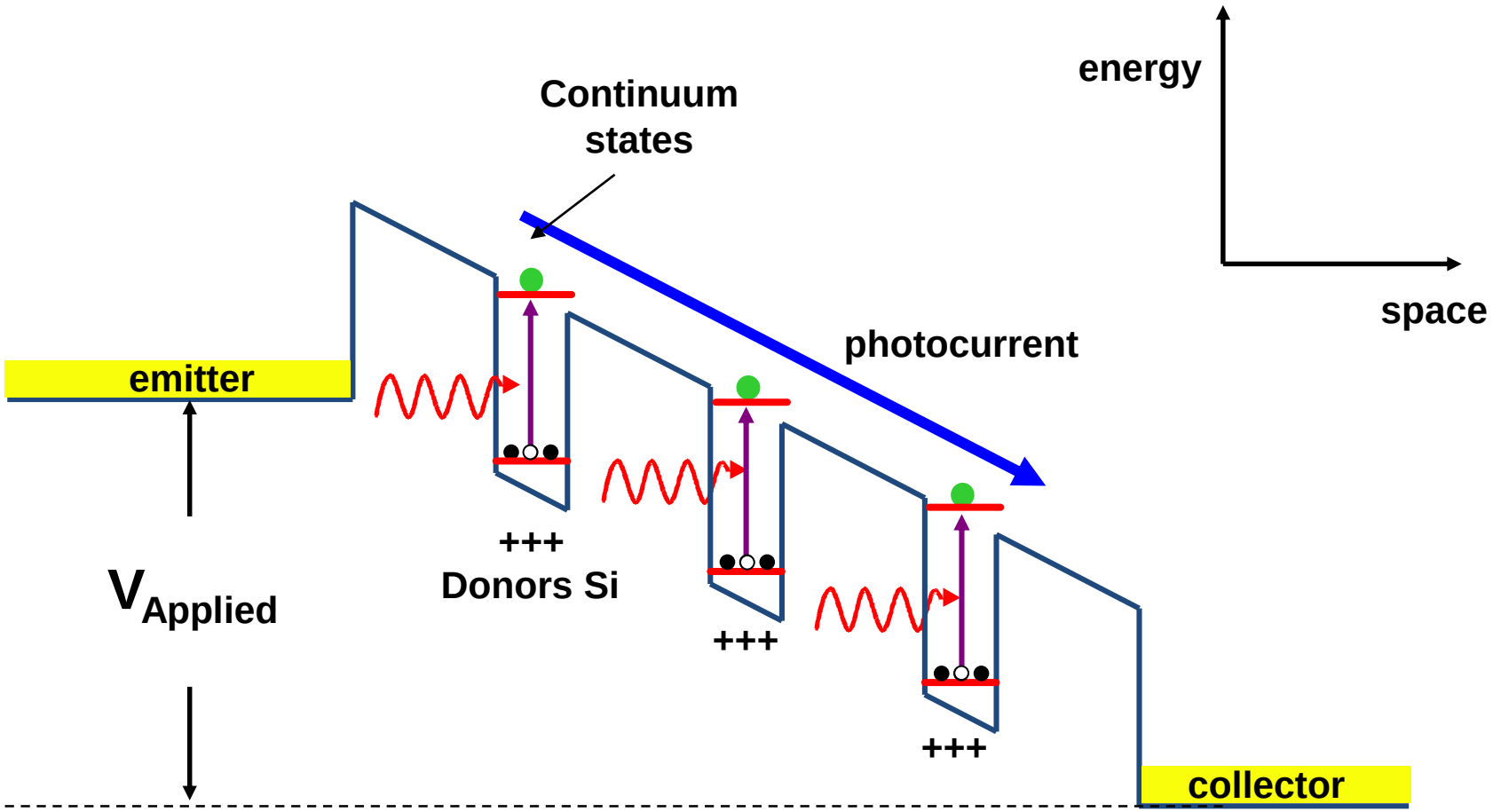
Quantum Well Infrared Photo-detector (QWIP)

Set of uncoupled quantum well with the excited states very close to the barrier top

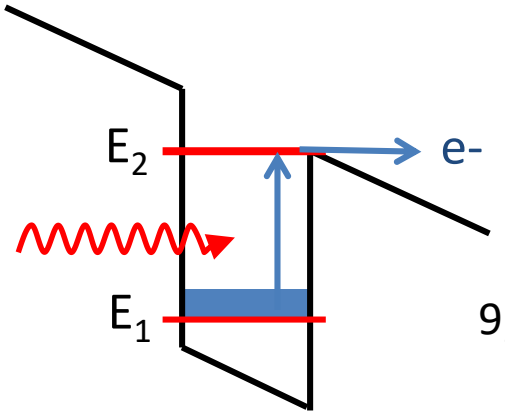




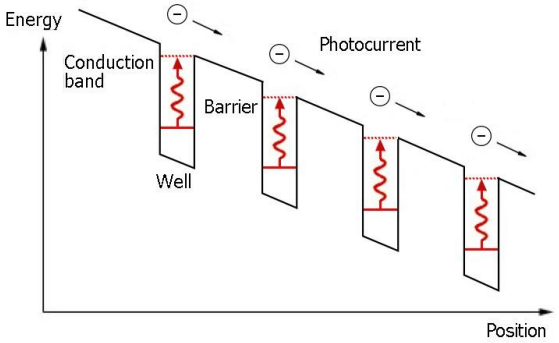
Quantum Well Infrared Photo-detector (QWIP)



Quantum well infrared photodetector (QWIP)



9μm detectors



B. F. Levine (Bell Labs, 1987)

THz (λ=100μm) ?

H. Schneider, H. C. Liu,
Quantum well infrared photodetectors: Physics and applications (Springer, Berlin, 2007).

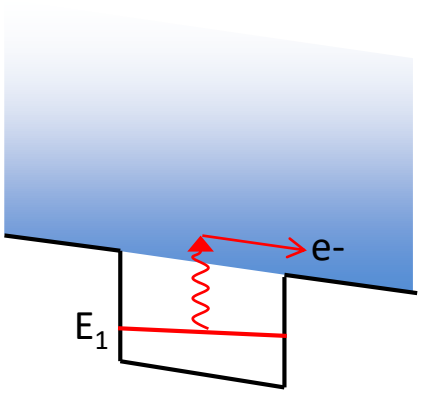
TeraHertz QWIP

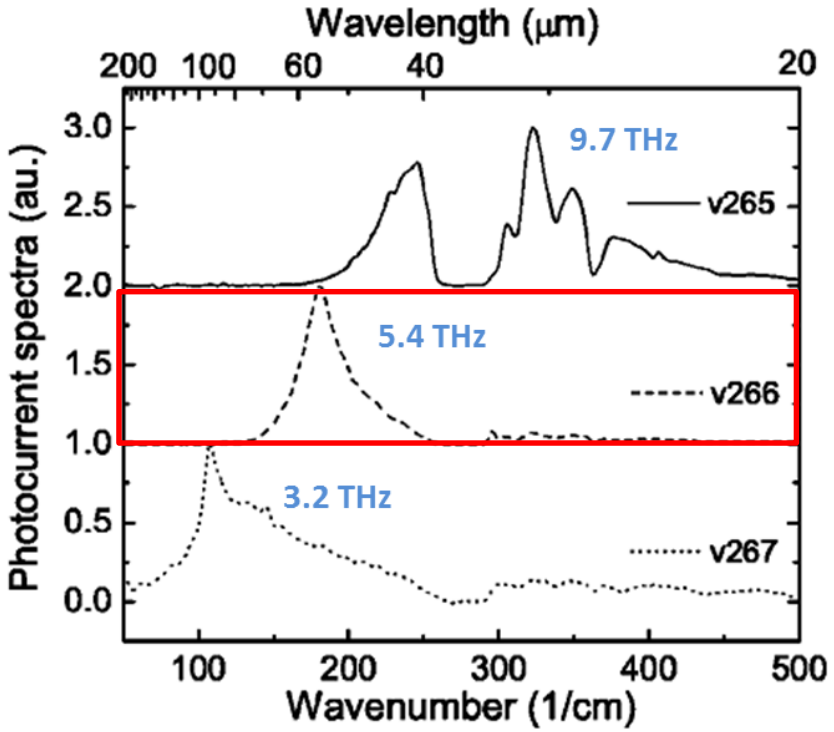
APPLIED PHYSICS LETTERS **86**, 231103 (2005)

Background-limited terahertz quantum-well photodetector

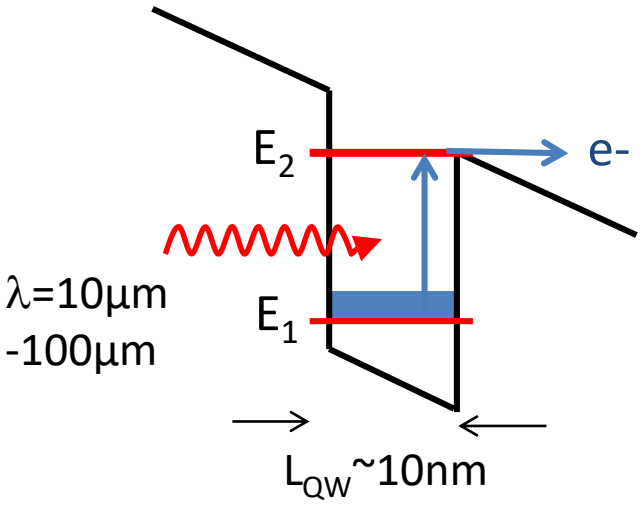
H. Luo,[a] H. C. Liu,[b] C. Y. Song, and Z. R. Wasilewski
Institute for Microstructural Sciences, National Research Council, Ottawa K1A 0R6, Canada

GaAs/AlGaAs quantum wells





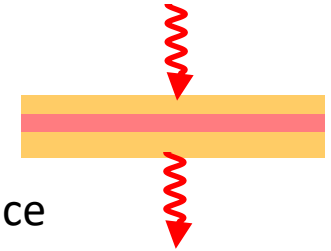
Main issues addressed



➔ Low quantum efficiency

2-3 % per well

➔ ISB selection rule



No absorption at normal incidence

➔ High dark current:

Low T operation to avoid the dark current

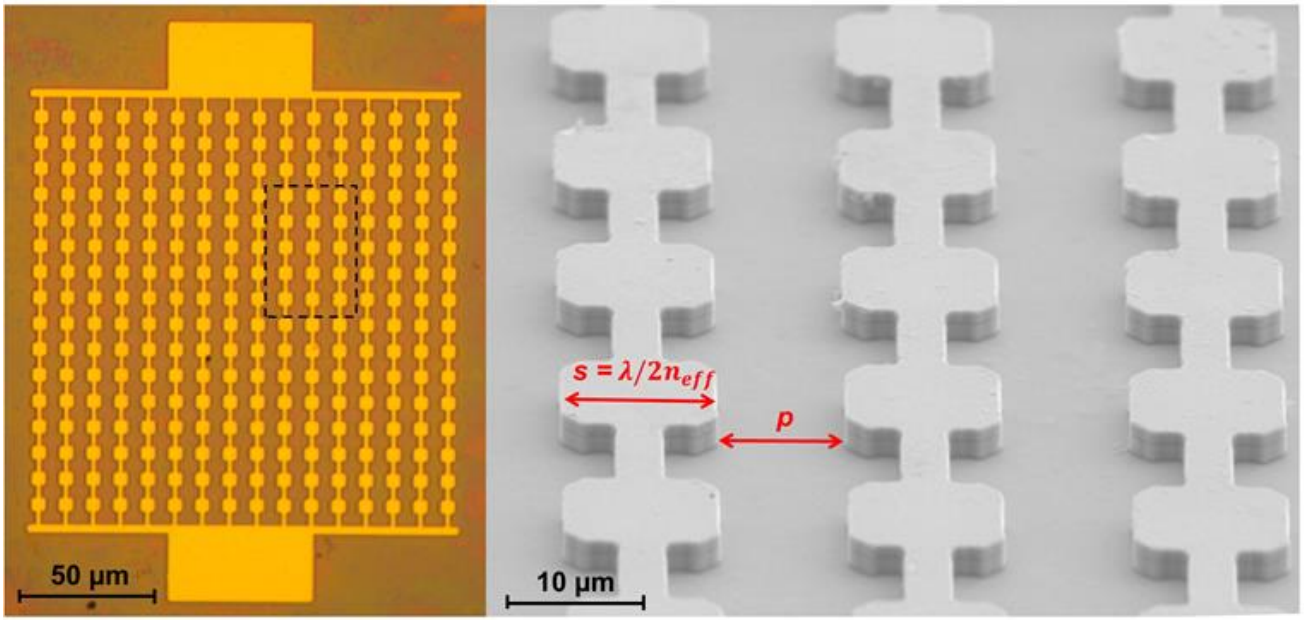
λ=10µm, T ~ 70K

THz: λ=100µm, T ~ 10K !

Image: SOFRADIR website

Our approach: Patch antenna arrays

p = 10 μm s= 6, 7, 8, 9 μm

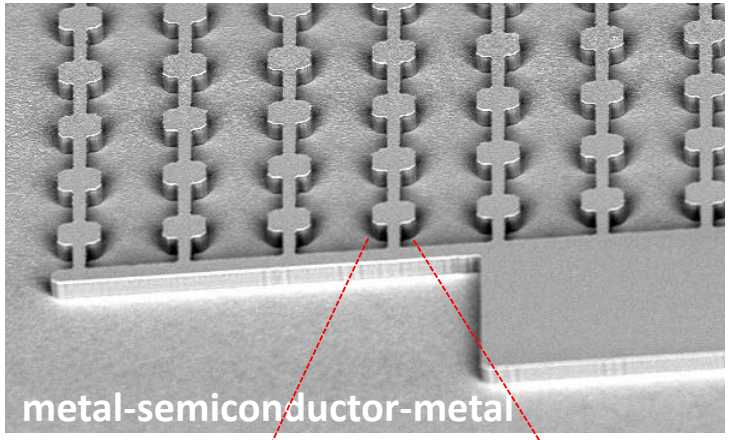


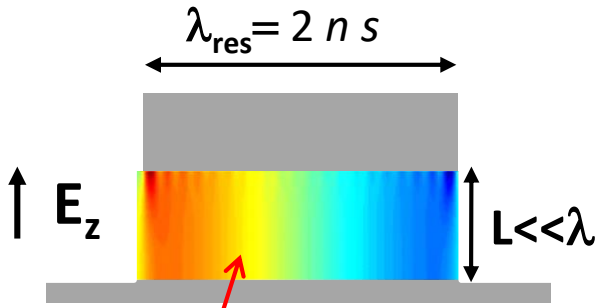
D. Palaferri et al.
APL. **106**, 161102 (2015)

Patch-antenna coupled microcavities

Quantum efficiency

→ Microcavity

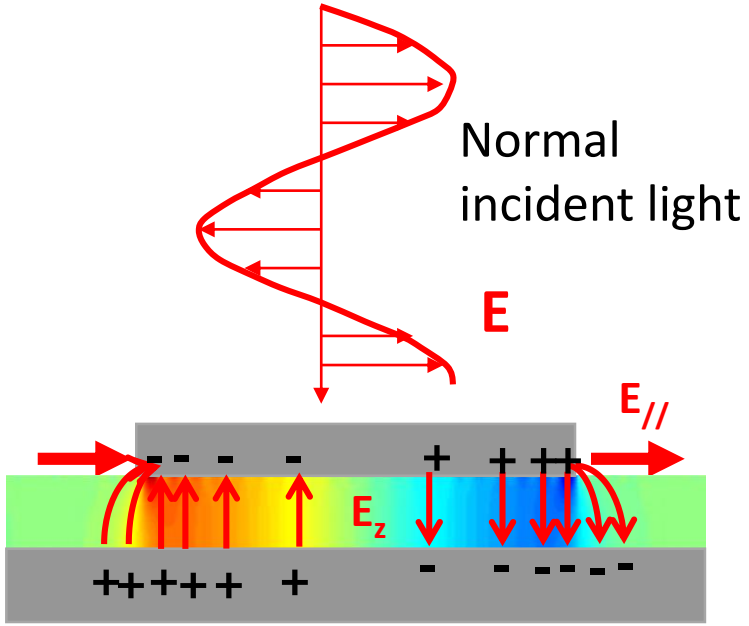




Standing wave
electromagnetic resonance

ISB selection rule

→ Quadrupole antenna

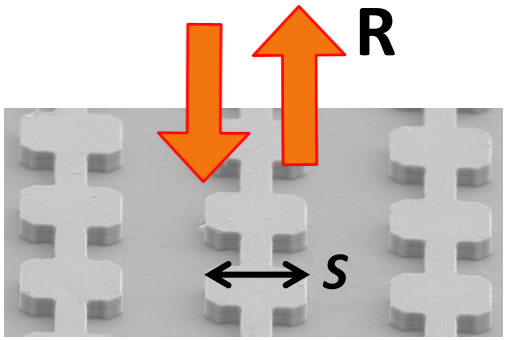


Capacity to rotate the polarization of the incident wave!

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

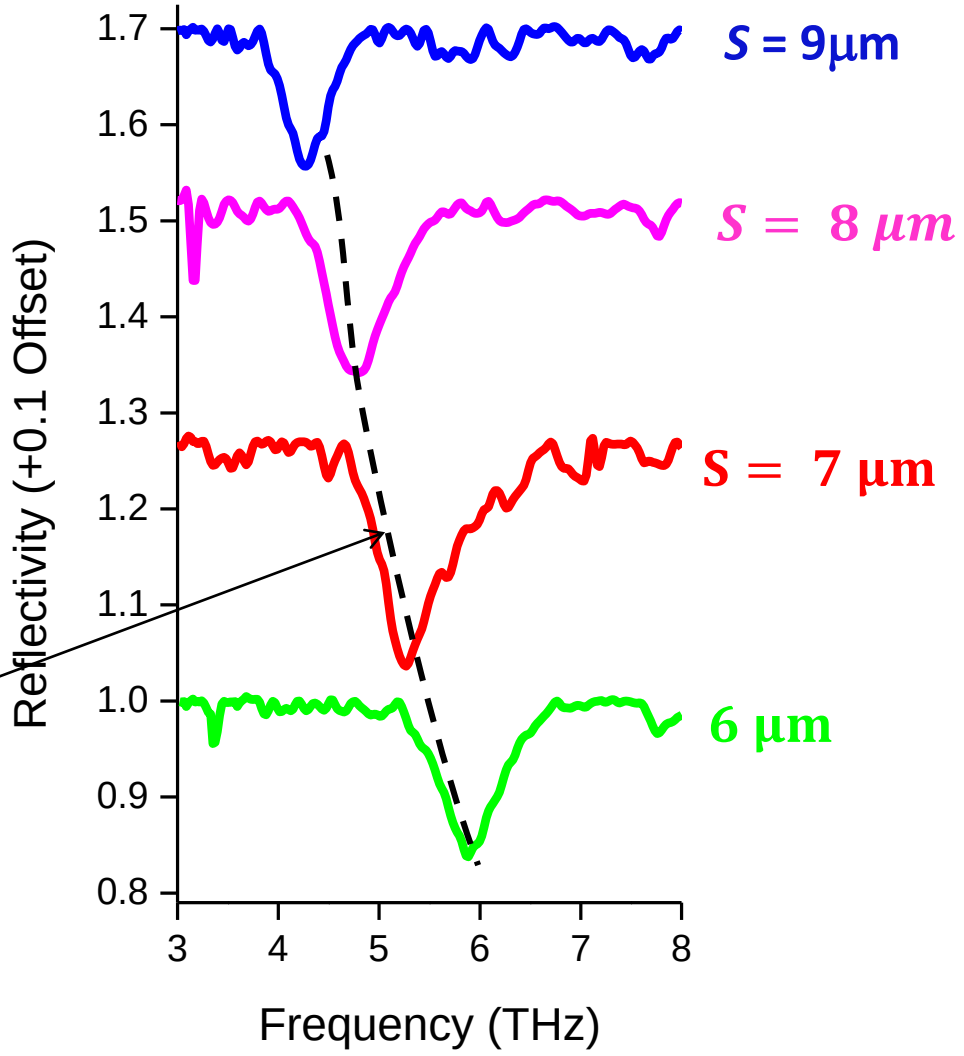
Opt. Express **18**, 13886 (2010); PRL **105,** 196402 (2010)

TeraHertz QWP: reflectivity measurements



Cavity mode tuning:

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

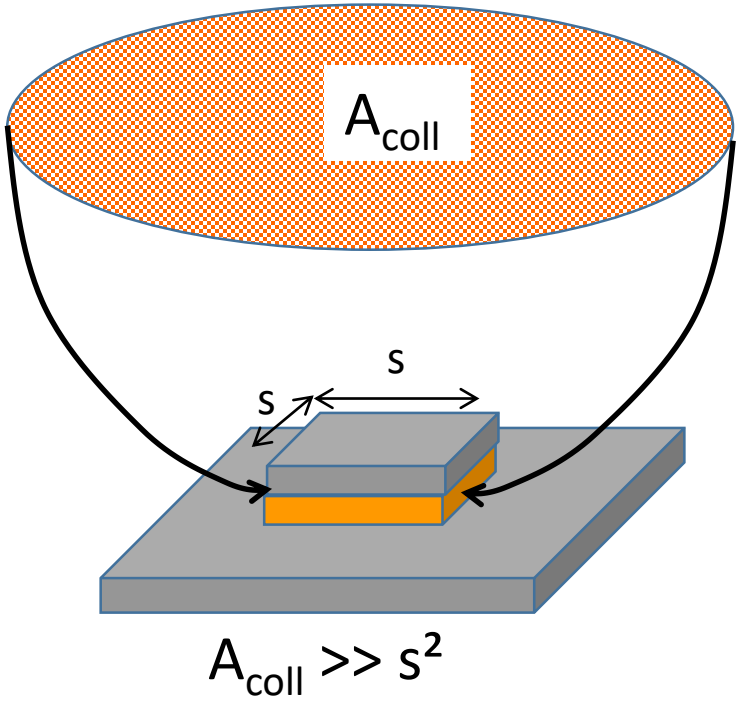


D. Palaferri et al.
APL. **106**, 161102 (2015)

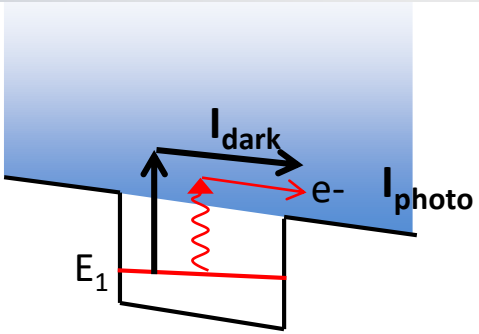
The benefits of antenna effects

High dark current

→ Antenna effect



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



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

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

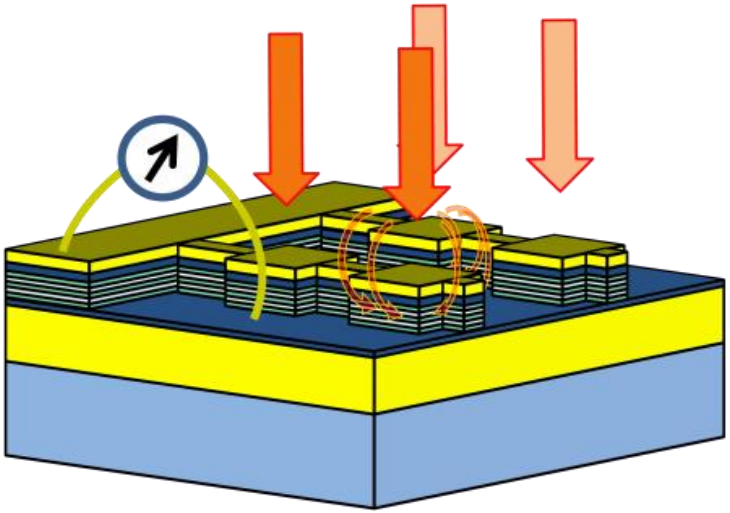
$A_{coll}/s^2 >> 1$

Increased signal to noise ratio!

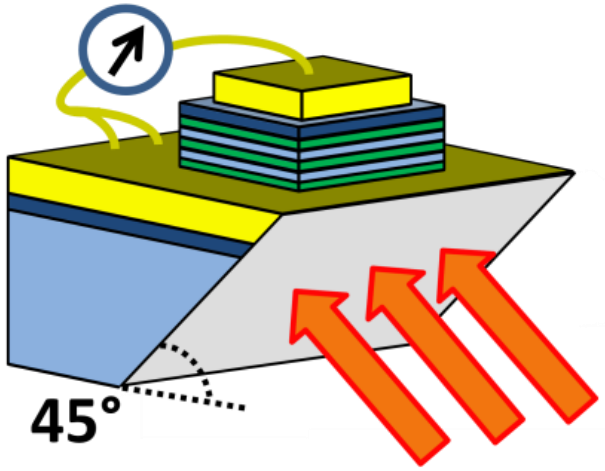
TeraHertz QWP: Comparative study

Two samples fabricated from the same wafer

Double-Metal geometry:
patch-antenna array

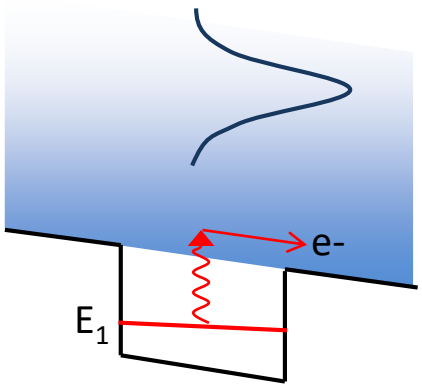


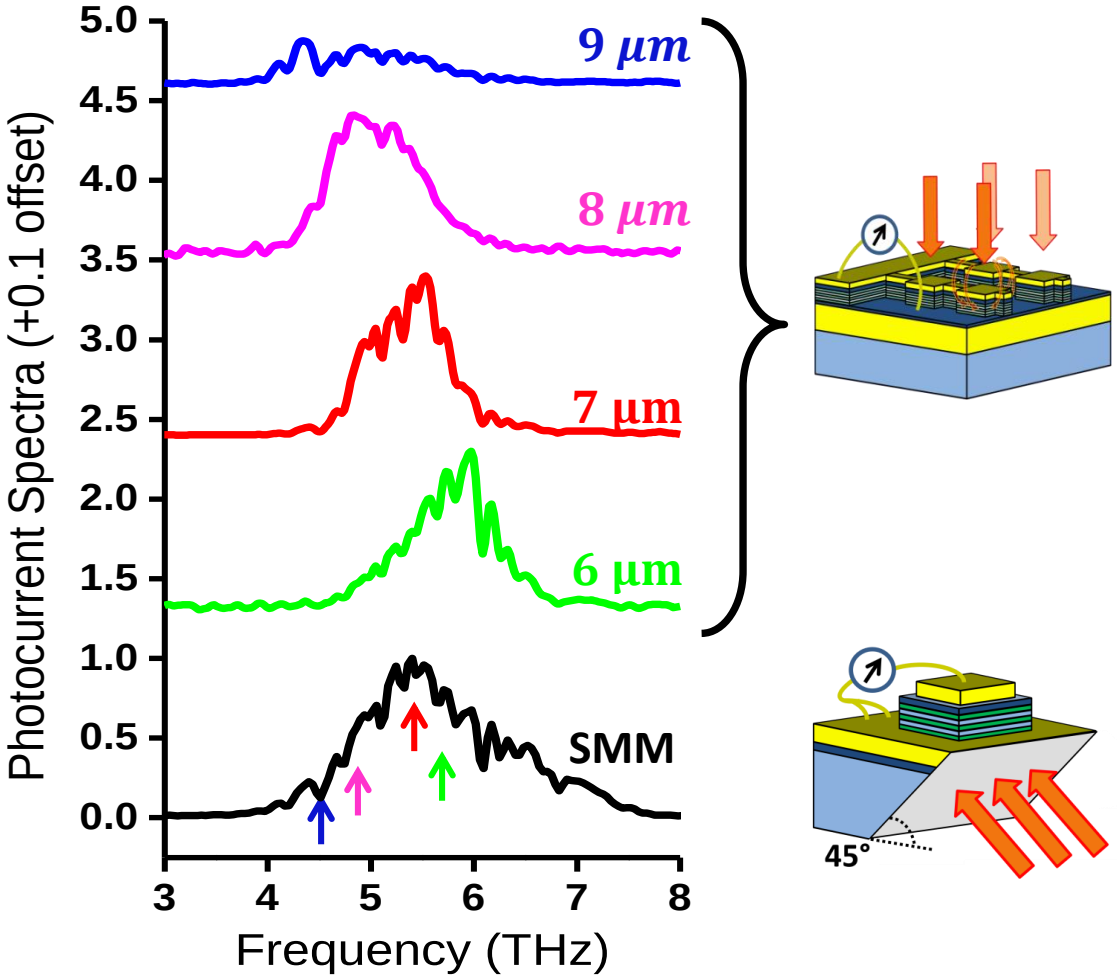
Single Metal Mesa
400x400 µm^2



TeraHertz QWP: photo-current response

T = 4K

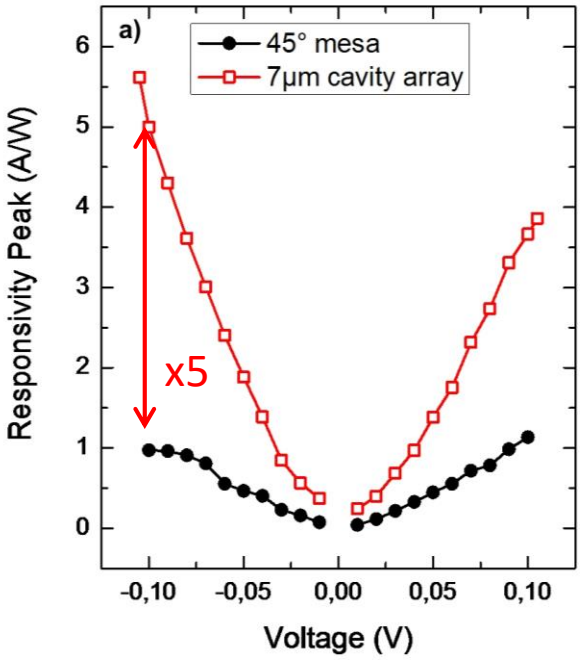




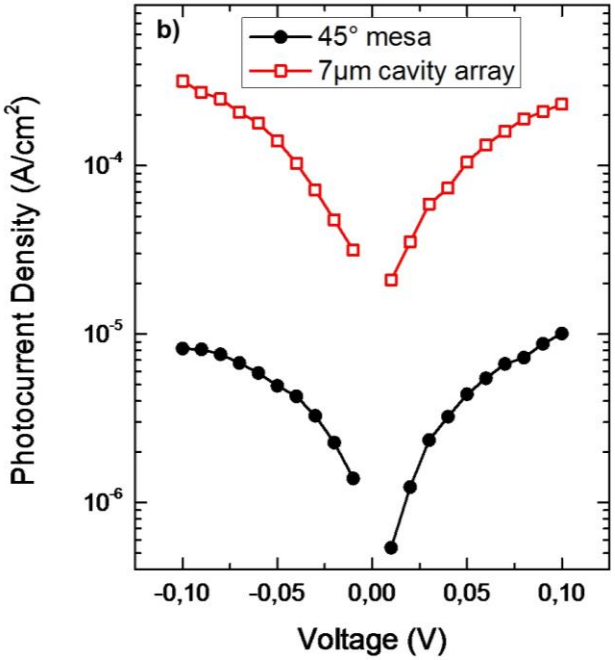
D. Palaferri et al.
APL. **106**, 161102 (2015)

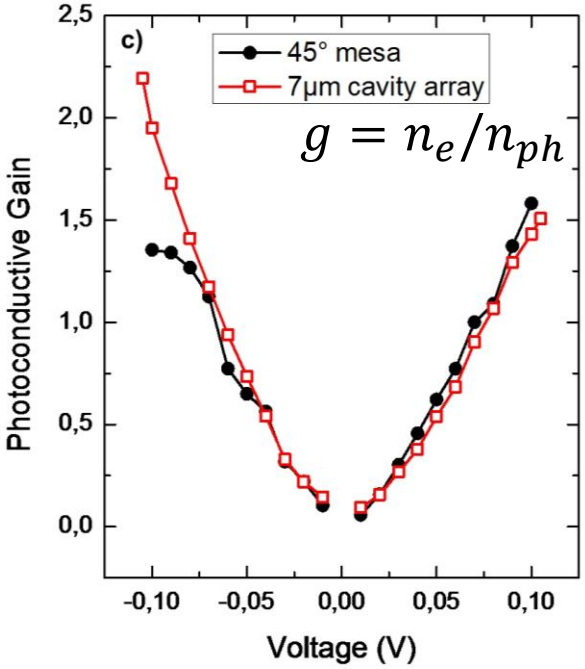
TeraHertz QWP: performance Analysis

Improved responsivity:
Microcavity



Higher photocurrent density
Antenna



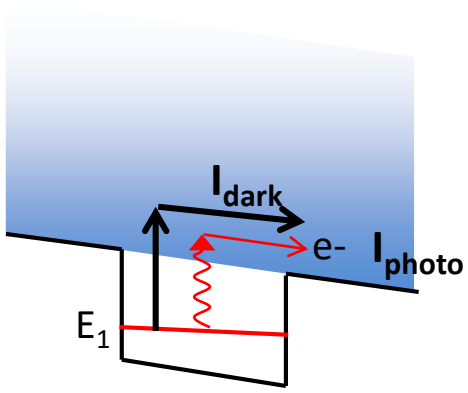


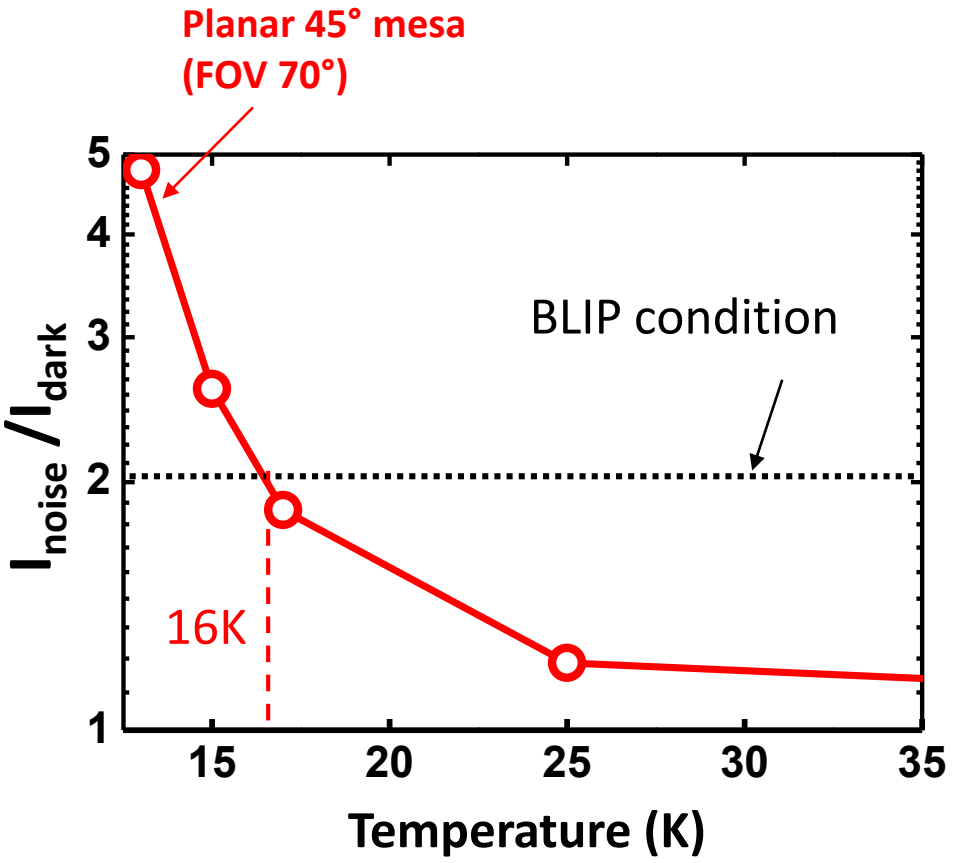
	D* BL	Optical NEP
7 μm – antenna QWIP	$1.7 \times 10^{11}\sqrt{Hz} \cdot cm/W$	$0.18\ \mathrm{p}W/\sqrt{Hz}$
doped Ge Bolometer (QMC)	$2.24 \times 10^{11}\sqrt{Hz} \cdot cm/W$	$2.23\ \mathrm{p}W/\sqrt{Hz}$

TeraHertz QWP: thermal performance

$I_{noise} = I_{dark} + I_{back}$

BLIP condition: $I_{noise} = 2\, I_{dark}(T_{BLIP})$

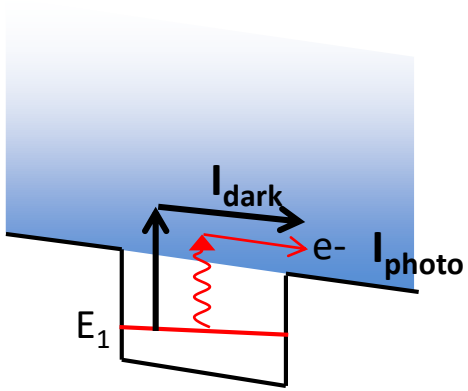


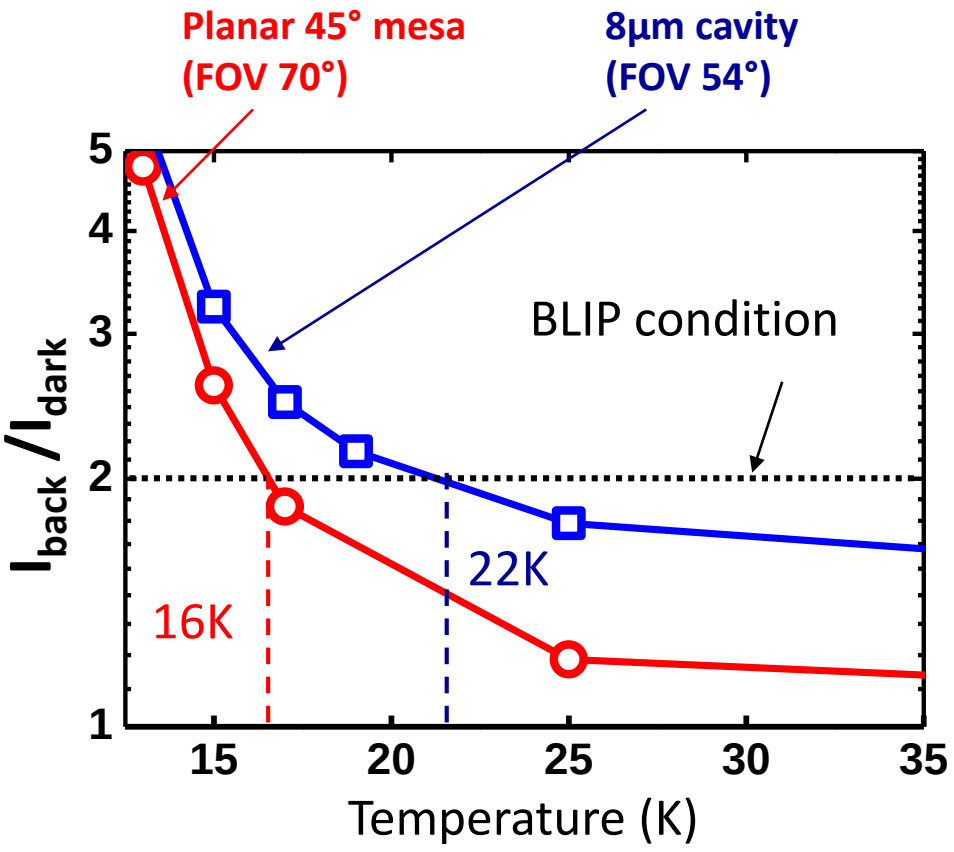


TeraHertz QWP: thermal performance

$I_{noise} = I_{dark} + I_{back}$

BLIP condition: $I_{noise} = 2\, I_{dark}(T_{BLIP})$





D. Palaferri et al.
APL. **106**, 161102 (2015)

Quantifying the temperature performance

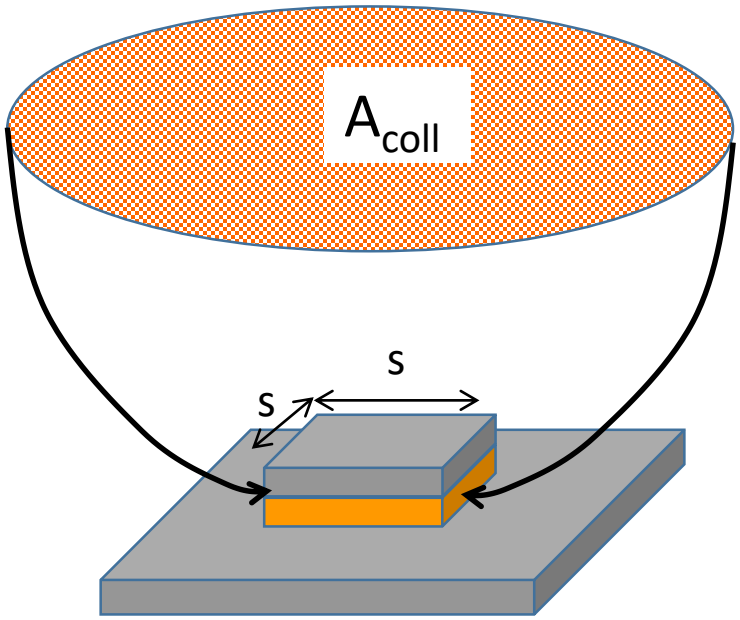
How the inherent detector properties vary with the device architecture?

Knowing T^0_{BLIP} (bare) what is T_{BLIP}(metamaterial) ?

Bare detector performance

$$T_{BLIP} \approx \frac{T^0_{BLIP}}{1 - \frac{k_B T^0_{BLIP}}{E_{12}} (\ln F - k)}$$

Transition energy



$A_{coll} >> s^2$

Focusing factor

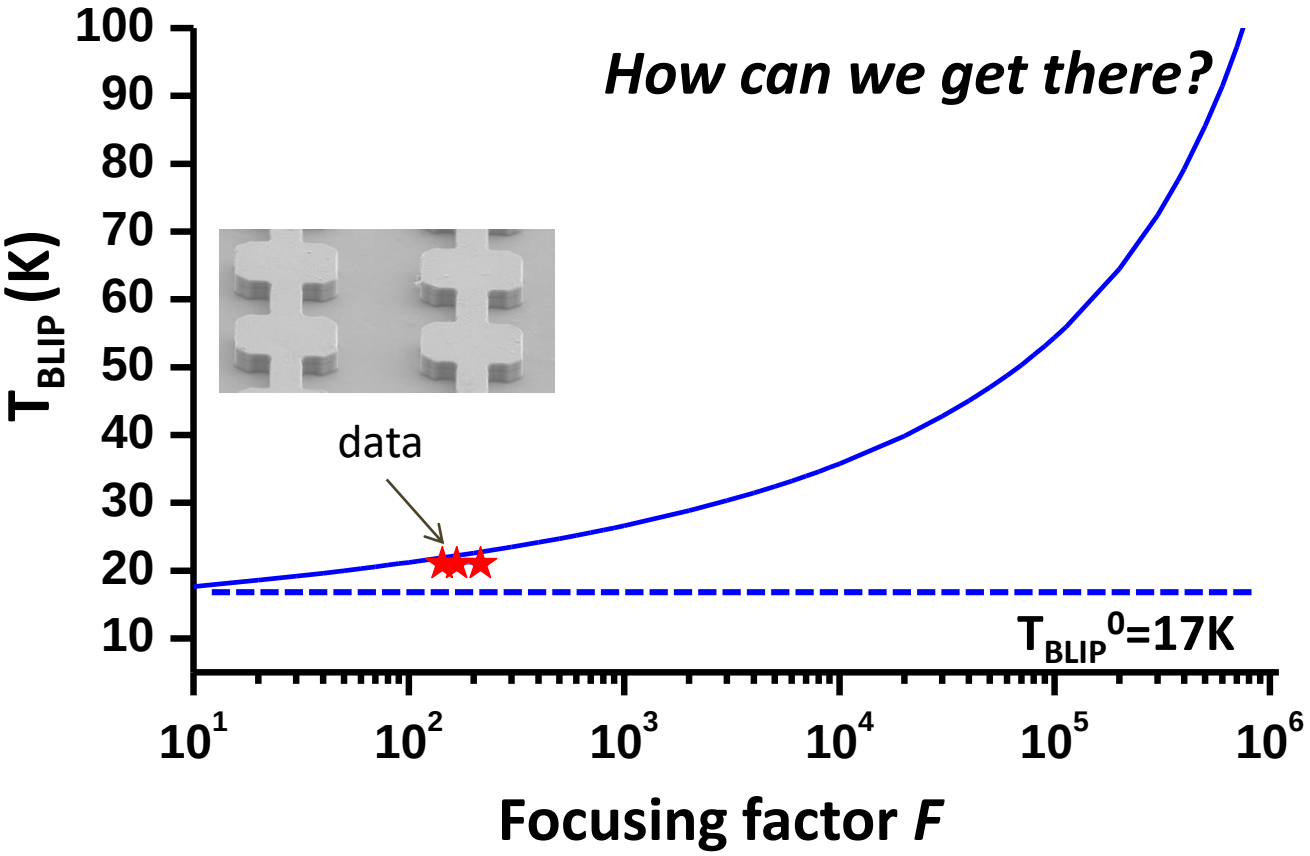
Quality factor

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

$V_{cav}=s^2L$

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

Focusing factor and temperature performance



Antenna effect

$$F = \frac{A_{col}\,\lambda_{res}}{V_{cav}}\,Q$$

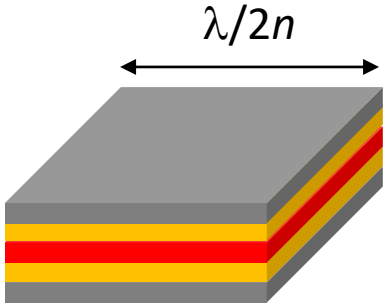
Electromagnetic confinement

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

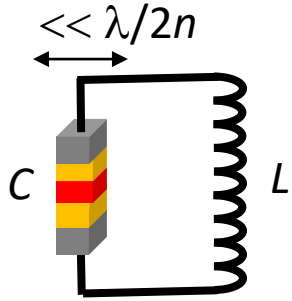
Going beyond the propagation limit

Moving from **optical macrocavities** to **electronic rsonators**

Square patch Antenna



$F \leq \frac{64}{\pi^2} Q^2$



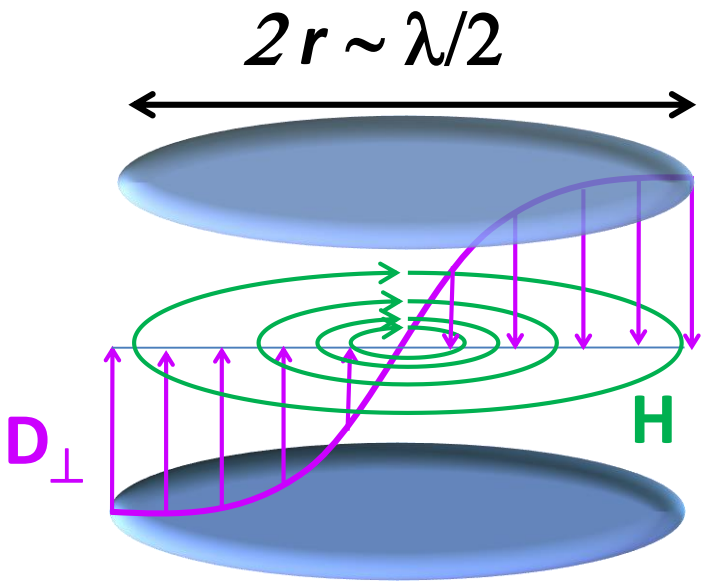
$F >> \frac{64}{\pi^2} Q^2$

$\nu_{res} = \frac{c}{2n\,s}$ **Optics**

Electronics $\nu_{res} = \frac{1}{2\pi\sqrt{LC}}$

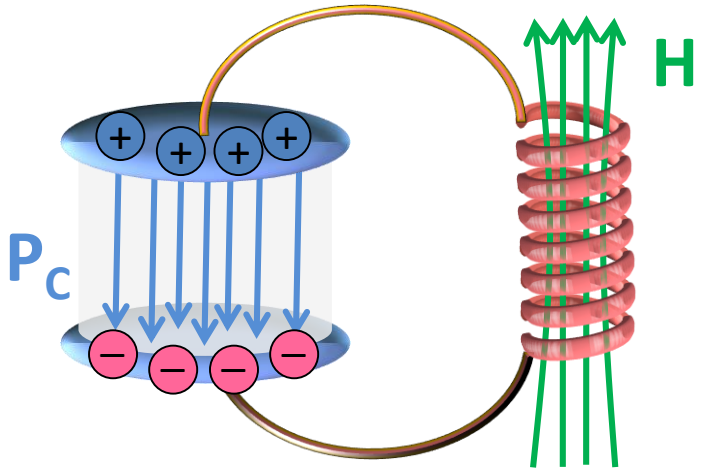
$$\text{rot}\,\mathbf{H} = -\frac{\partial \mathbf{D}}{\partial t} + \mathbf{j}$$

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



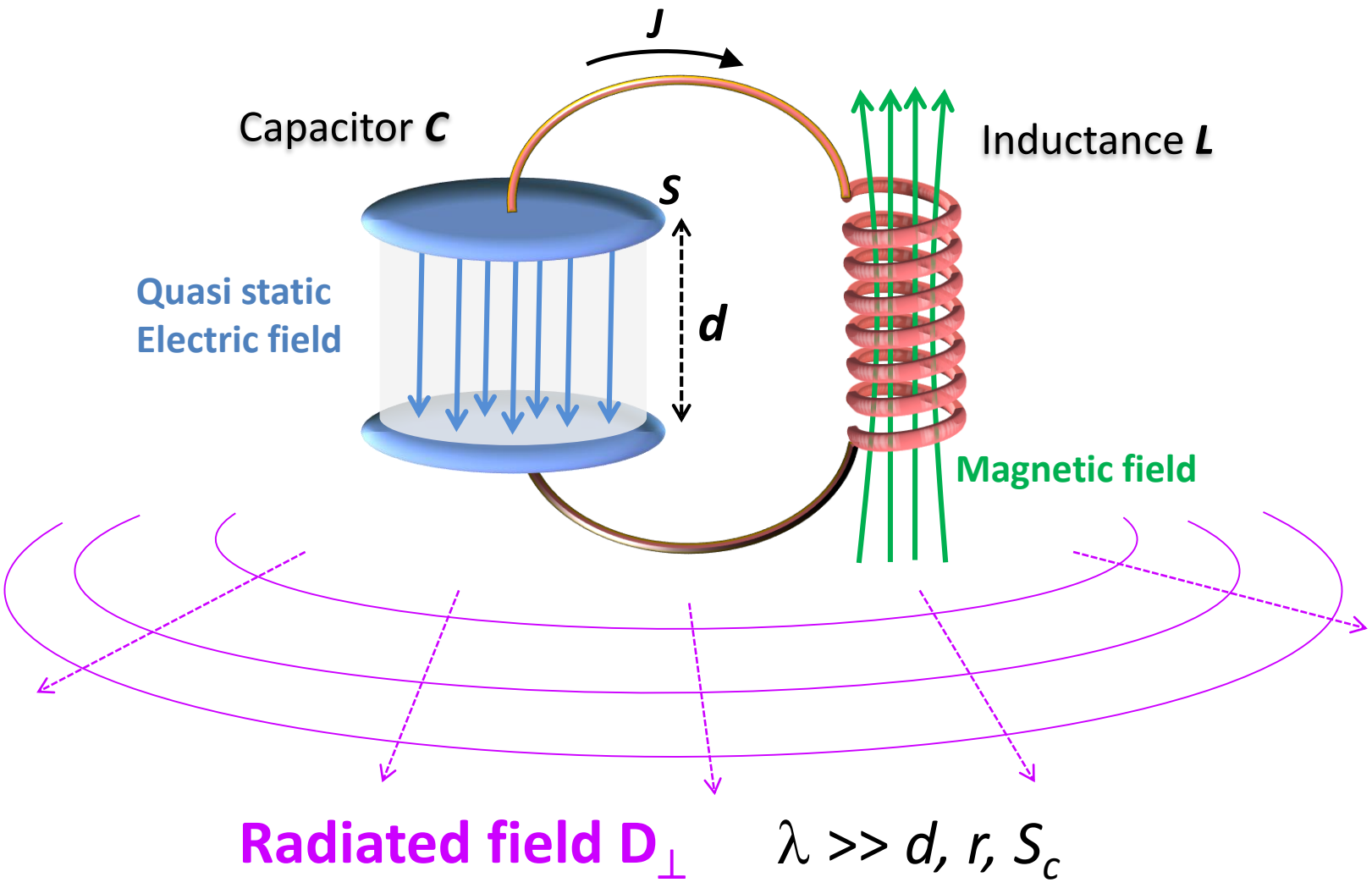
Optics

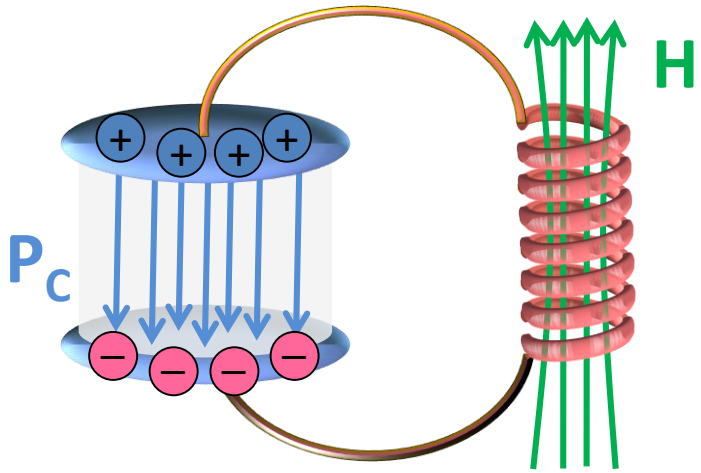
$$\int \frac{\mathbf{D}_\perp^2}{2\varepsilon_0} d^3r + \int \frac{\mu_0 \mathbf{H}^2}{2} d^3r + \int \frac{\mathbf{P}_C^2}{2\varepsilon_0 \varepsilon} d^3r$$



Electronics

$$\int \frac{\mathbf{D}_\perp^2}{2\varepsilon_0} d^3r + \int \frac{\mu_0 \mathbf{H}^2}{2} d^3r + \int \frac{\mathbf{P}_C^2}{2\varepsilon_0 \varepsilon} d^3r$$


J
Capacitor C
Inductance L
S
d
Quasi static
Electric field
Magnetic field
Radiated field D⊥
λ >> d, r, Sc

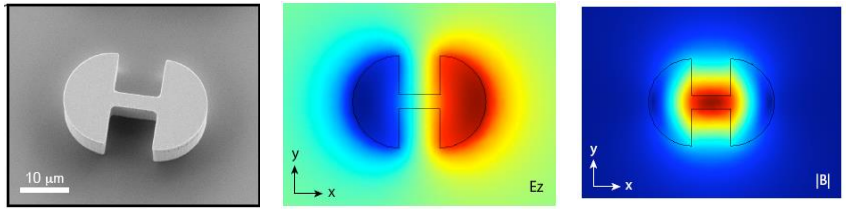


Electronics

$$\int \frac{\mathbf{D}_{\perp}^2}{2\varepsilon_0} d^3r + \int \frac{\mu_0 \mathbf{H}^2}{2} d^3r + \int \frac{\mathbf{P}_C^2}{2\varepsilon_0 \varepsilon} d^3r$$

Going beyond the propagation limit

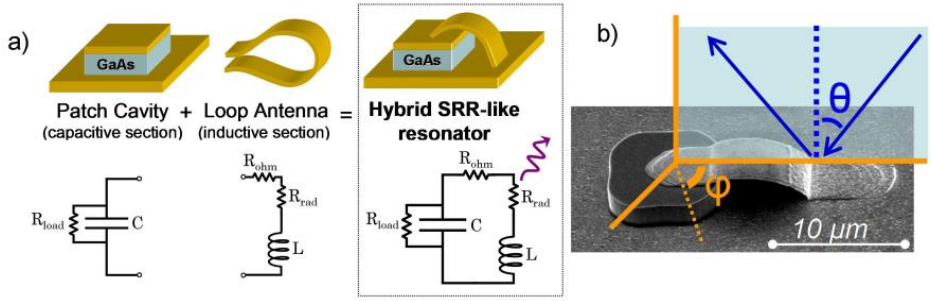
- LC-like patch cavities



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

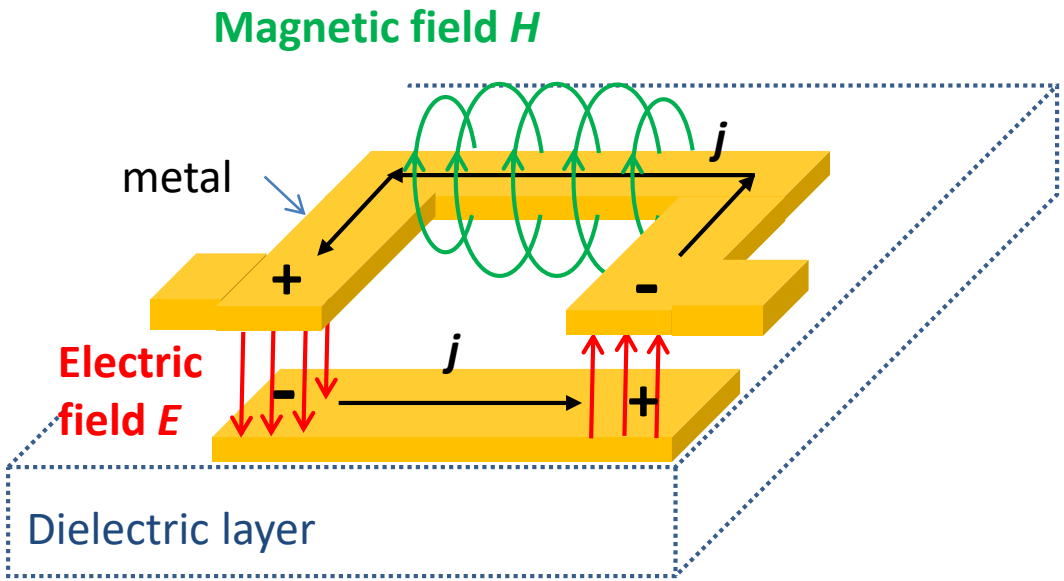
J. Faist's group (ETH Zurich)

- « Inverted » meta-materials



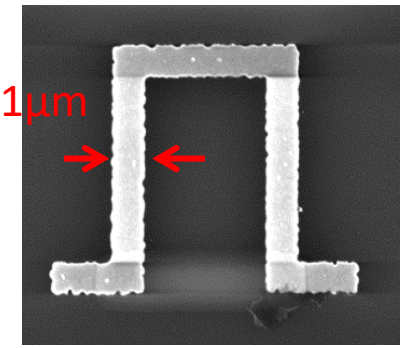
B. Paulillo et al.
Opt. Express, **22**, 21302 (2014)

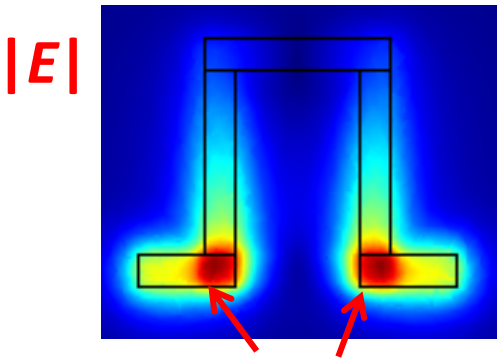
Metamaterial Detector



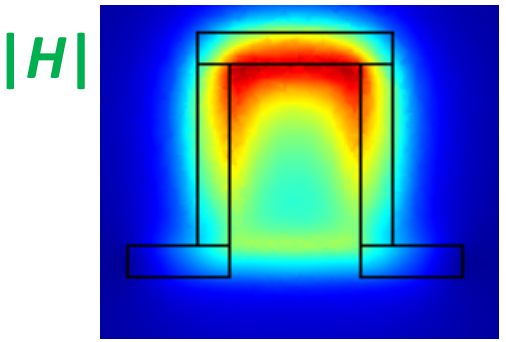
Advantages:

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



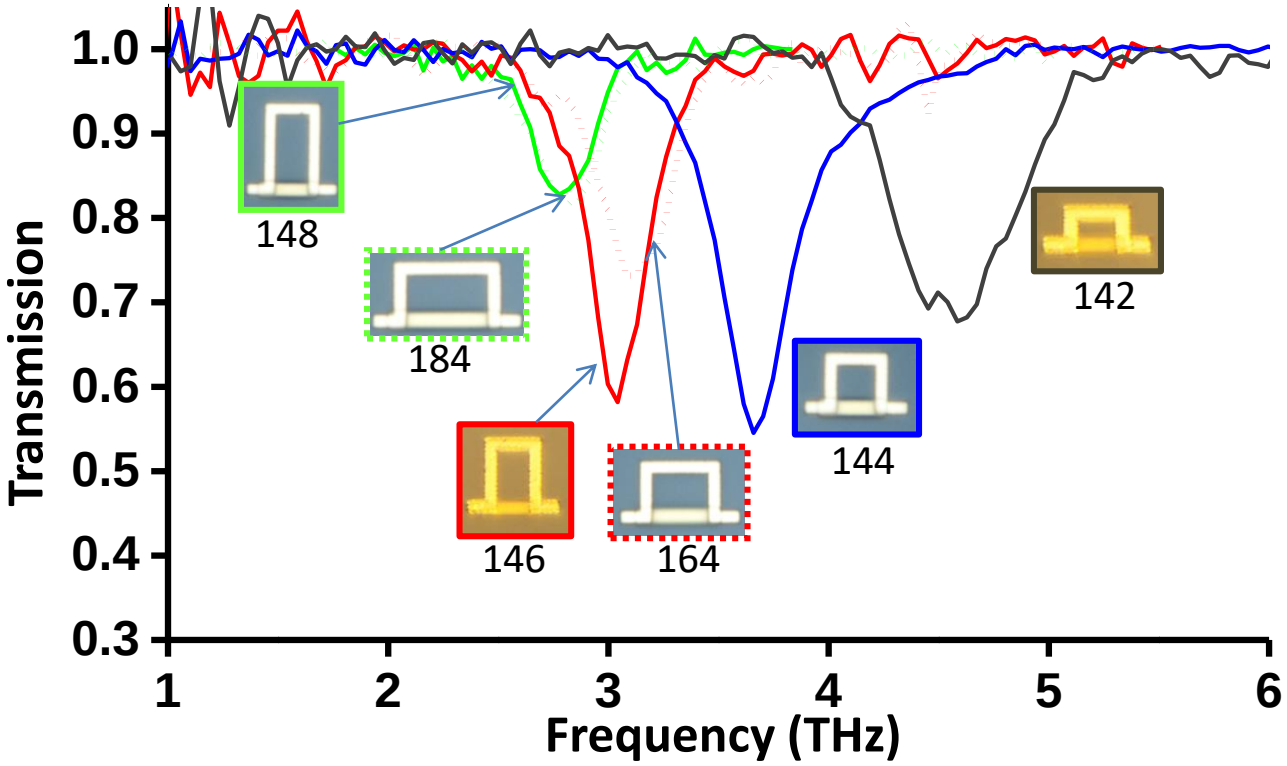


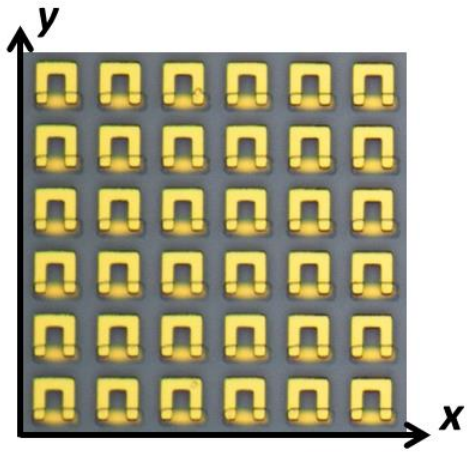
sub-wavelength capacitors



Y. Todorov *et al. Opt. Express*. **23**(13), 16839-16845 (2015)

Transmission: tuning of the inductor size





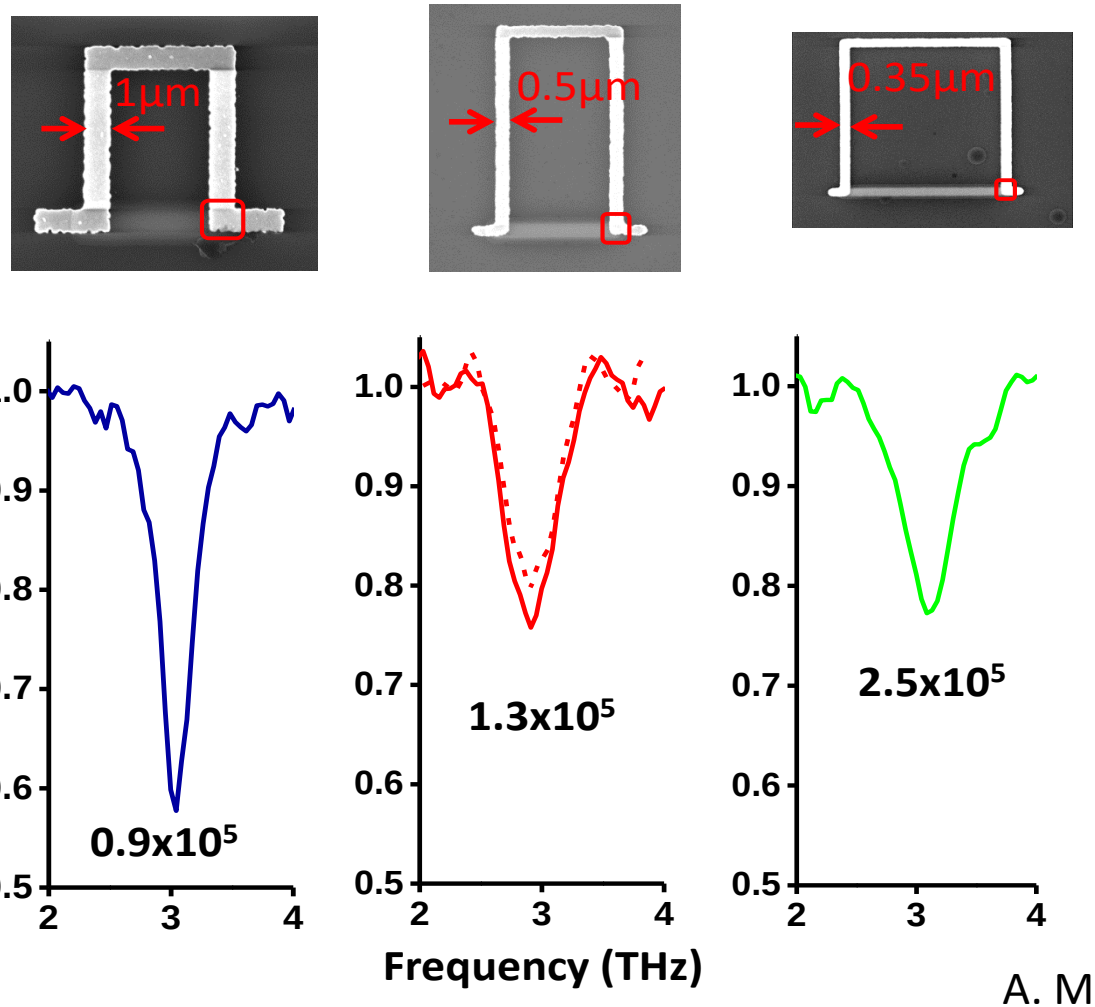
A. Mottaghizadeh, (unpublished)

Tuning the capacitor

Smaller capacitors → Smaller volume of interaction while keeping the resonance at 3THz

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

C↓ L↑

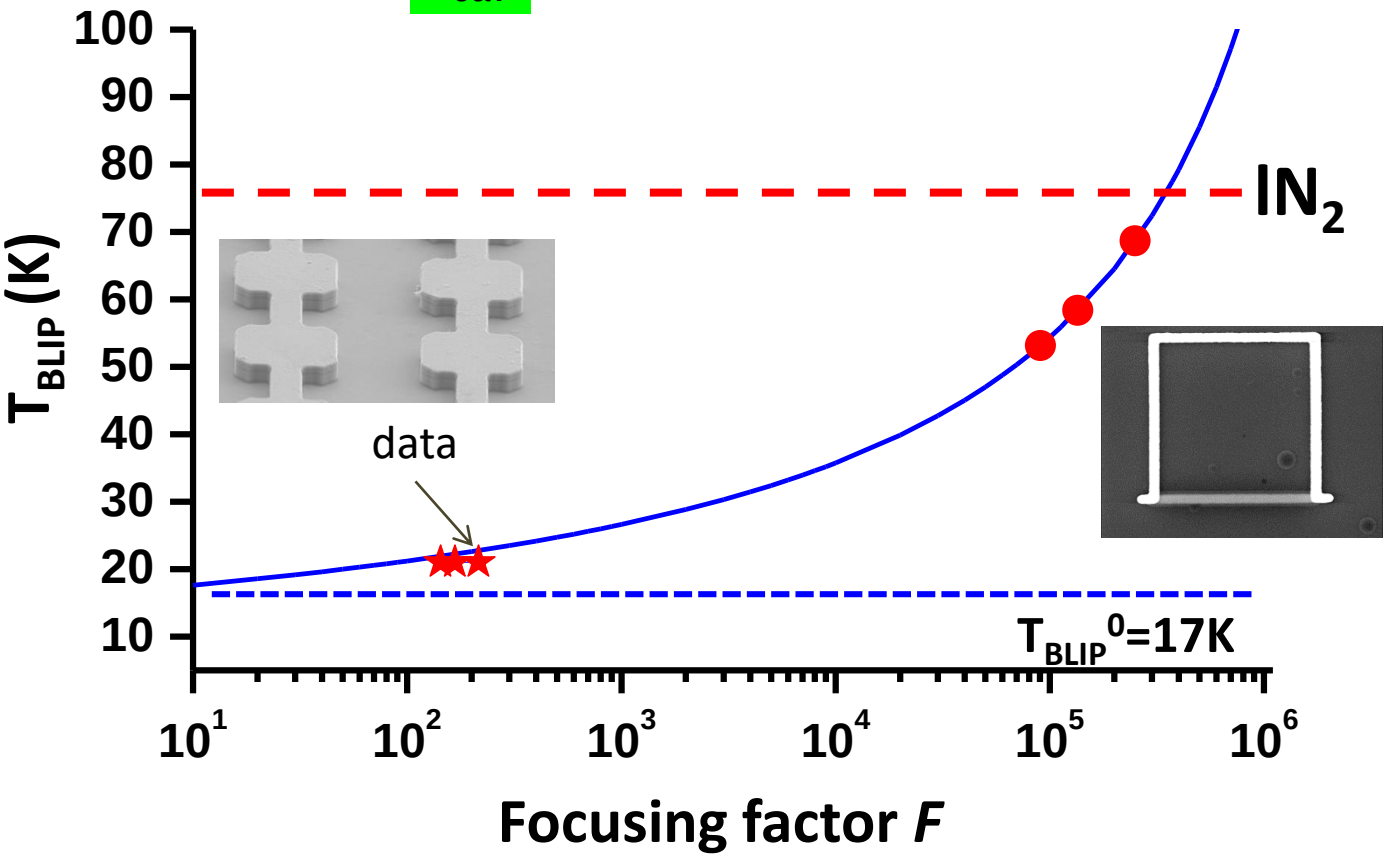


Resonant absorption in nanometers volumes

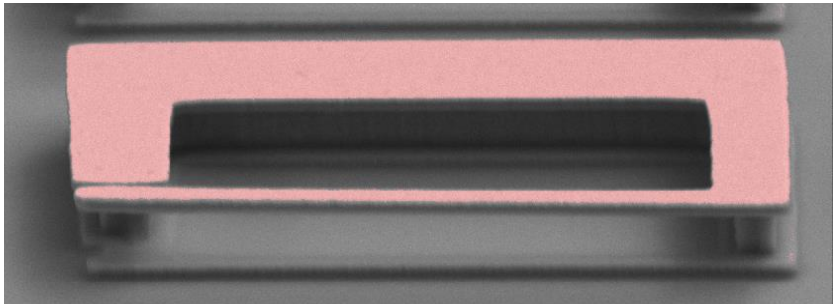
A. Mottaghizadeh, unpublished

Focusing factor for LC structures

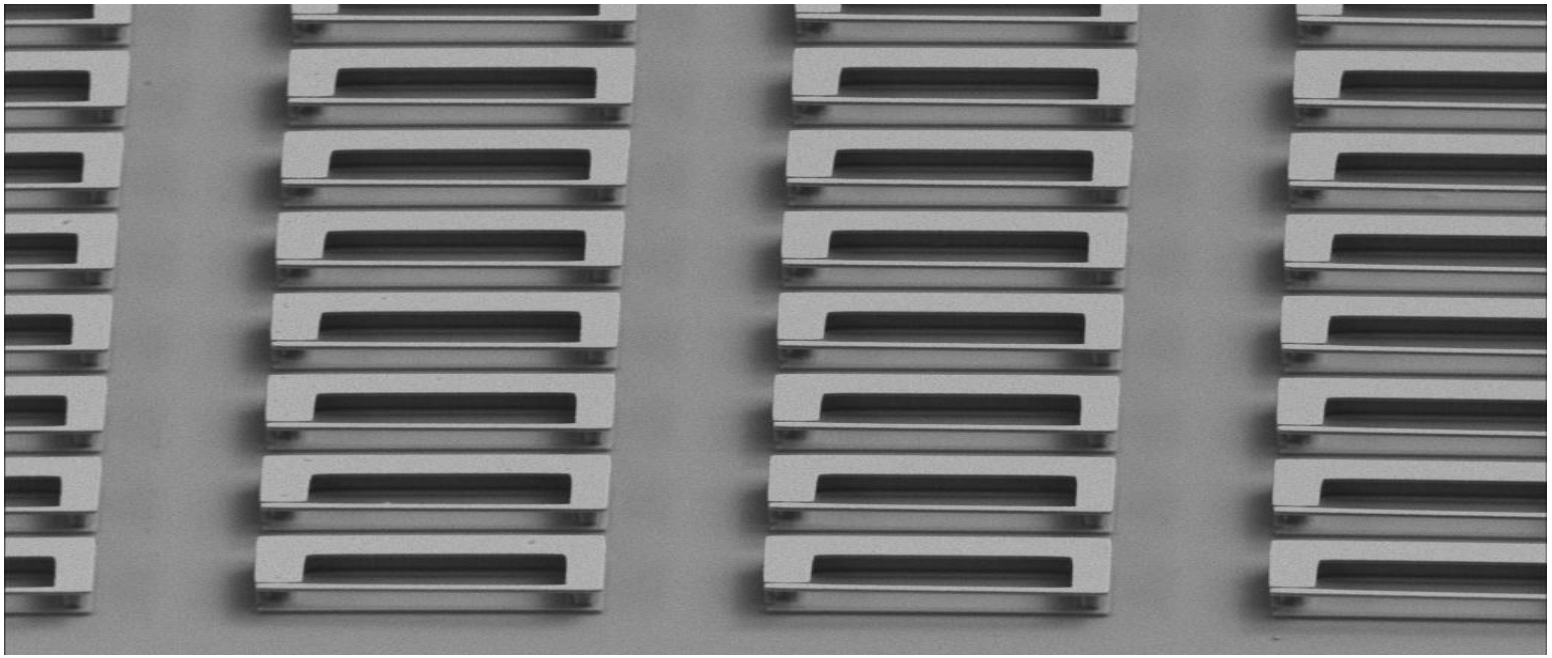
$$F = \frac{A_{col}\lambda_{res}}{V_{cav}}Q$$



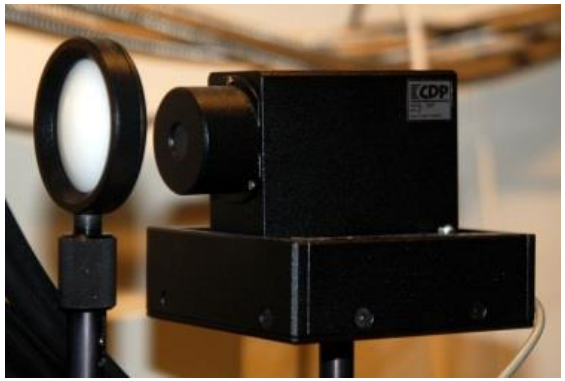
Liquid Nitrogen operation for quantum THz detectors !?

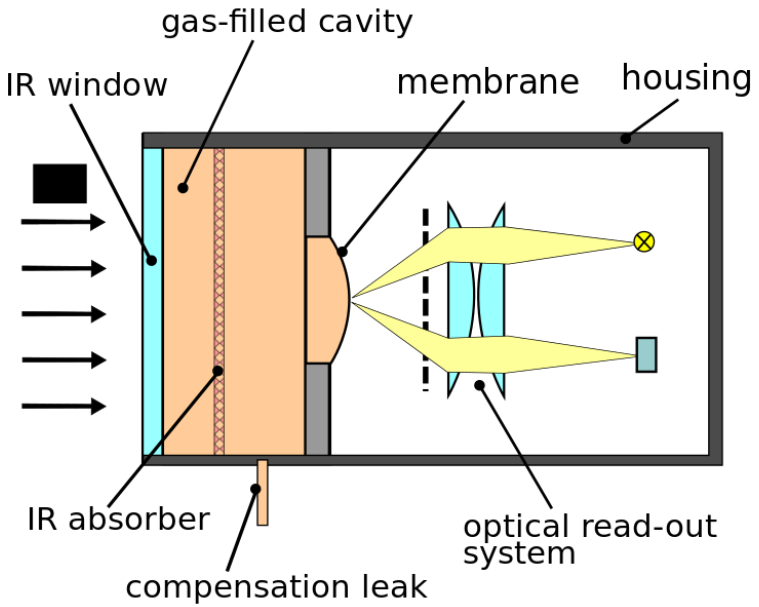


Optomechanical THz detection



The Golay cell: an optomechanical device

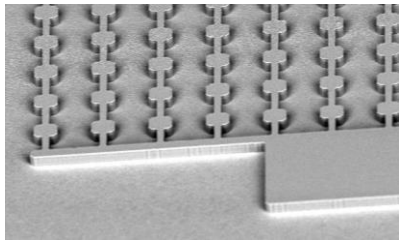


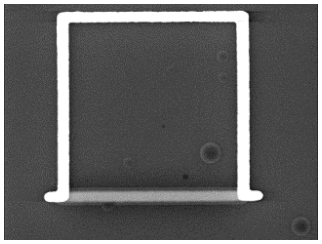


From Wikipedia

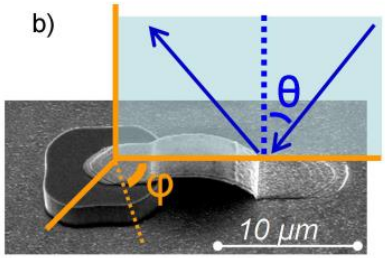
Metamaterials + optomechanics

THz metamaterials (for devices)

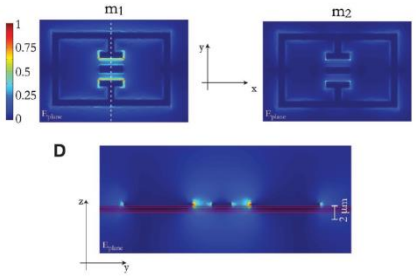




D. Palaferri et al., APL. **106**, 161102 (2015)
D. Palaferri et al., New J. Phys. **18** 113016 (2016)

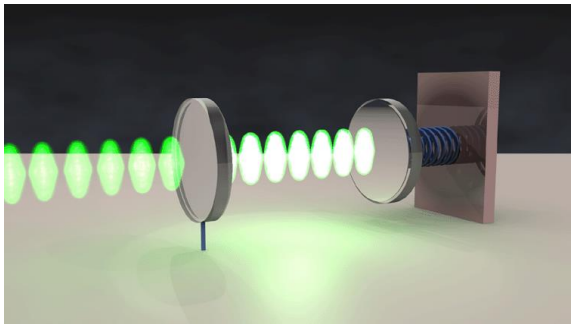


B. Paulillo et al. Opt. Express, **22**, 21302 (2014)

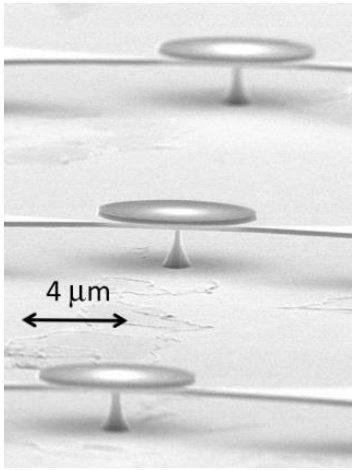


G. Scalari et al. Science, **335**, 1323 (2012)

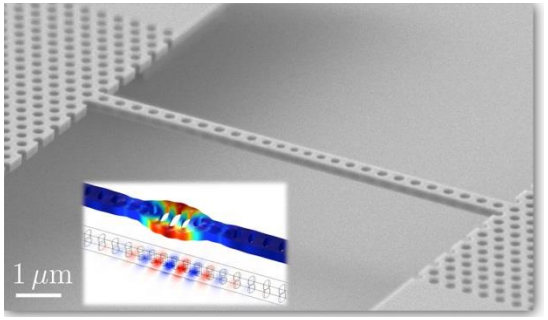
Optomechanics



I.Favero, and K. Karrai *Nature Phot.* (2009)

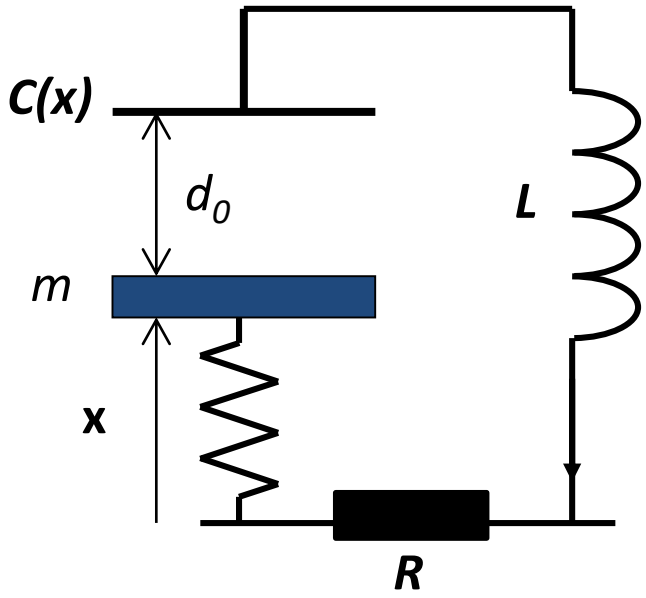


Courtesy I.Favero



C. Galland *et al.*,
Phys. Rev. Lett. 112, 143602 (2014)

Optomechanics with THz metamaterials

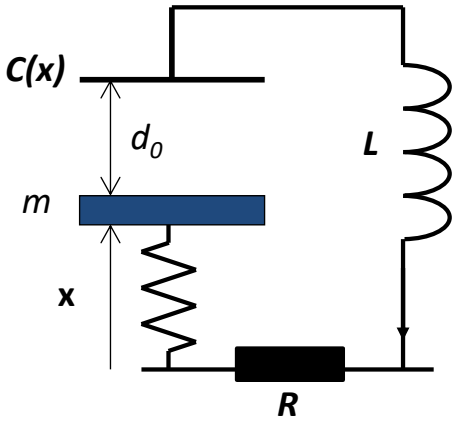


A device with 2 oscillators operating at 2 well distinct frequencies:

$$\omega_{LC} = \frac{1}{\sqrt{LC}} \approx 3THz$$

$$\omega_M = \sqrt{\frac{K}{m}} \approx 1MHz$$

Optomechanics with THz metamaterials



THz energy coupled into the LC

Dissipative term

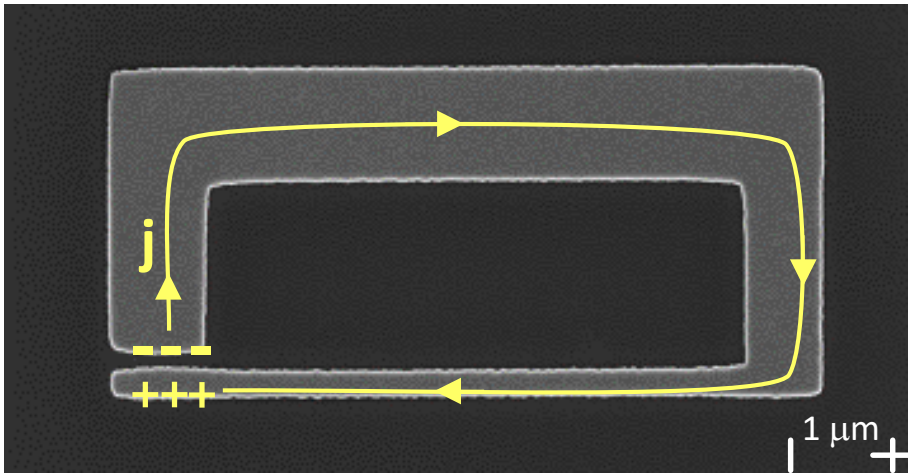
$$\frac{d^2x}{dt^2} + \frac{\omega_M}{Q}\frac{dx}{dt} + \omega_M^2 x = \frac{W_{THz}(t)}{m_{eff}\, d_0}$$

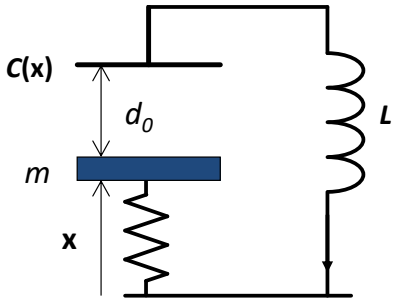
Cantilever mass

Capacitor spacing

Optomechanics with THz metamaterials

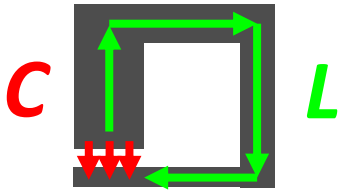
Split ring resonator with a movable arm





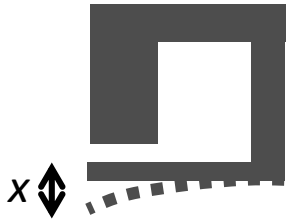
THz resonator

$$f_{LC} = \frac{1}{2\pi\sqrt{LC}} = 3 \ THz$$



+

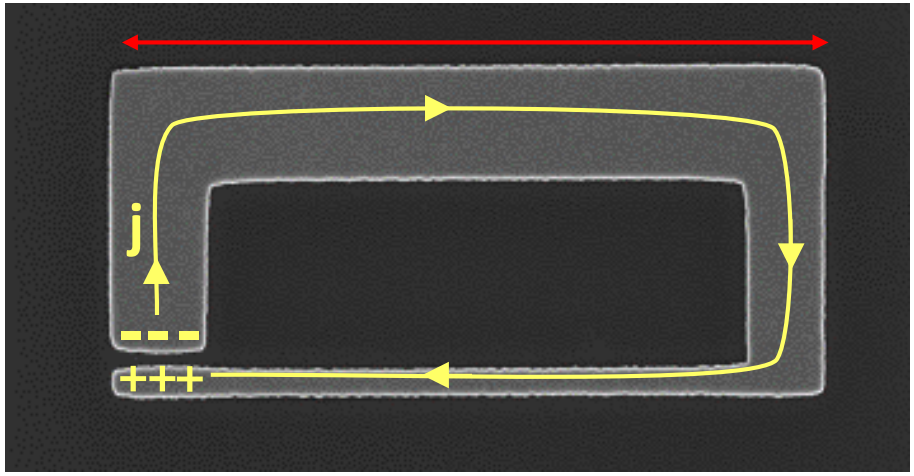
Mechanical resonator

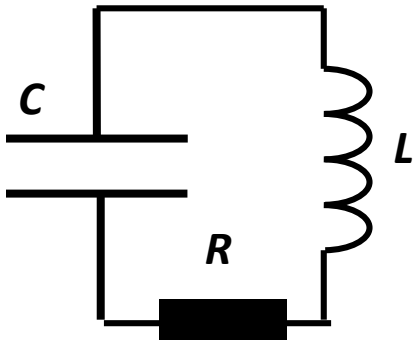


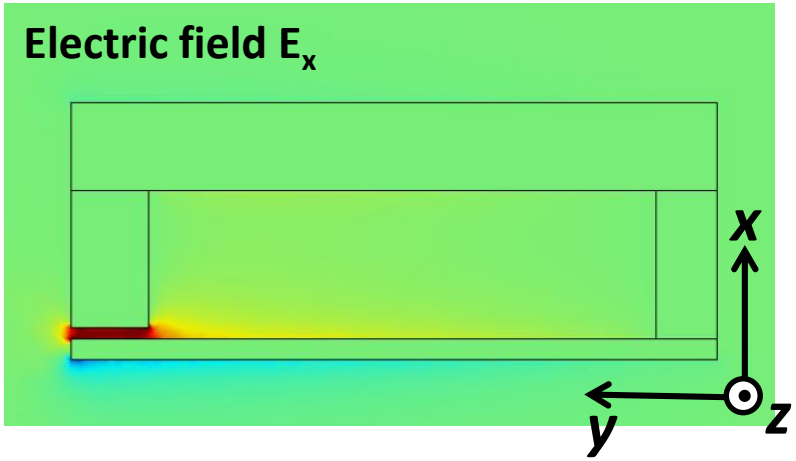
$$f_M = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = 1 \ MHz$$

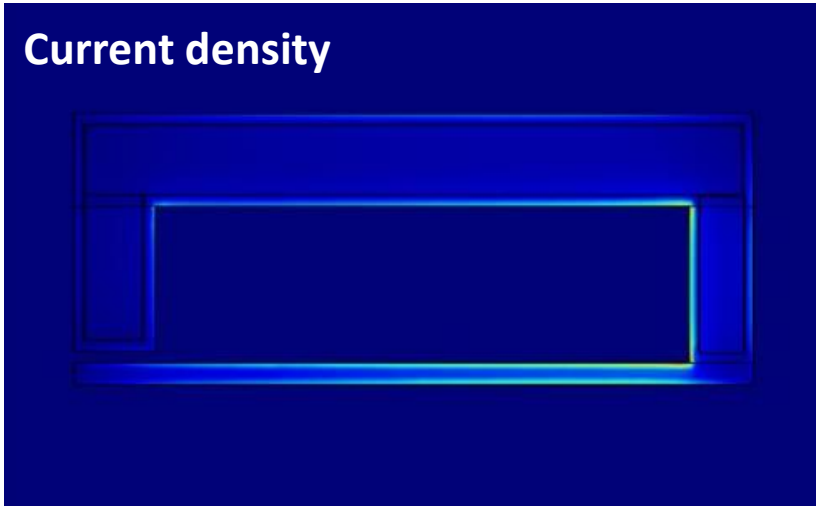
THz optomechanical detector: optical part

L=18µm



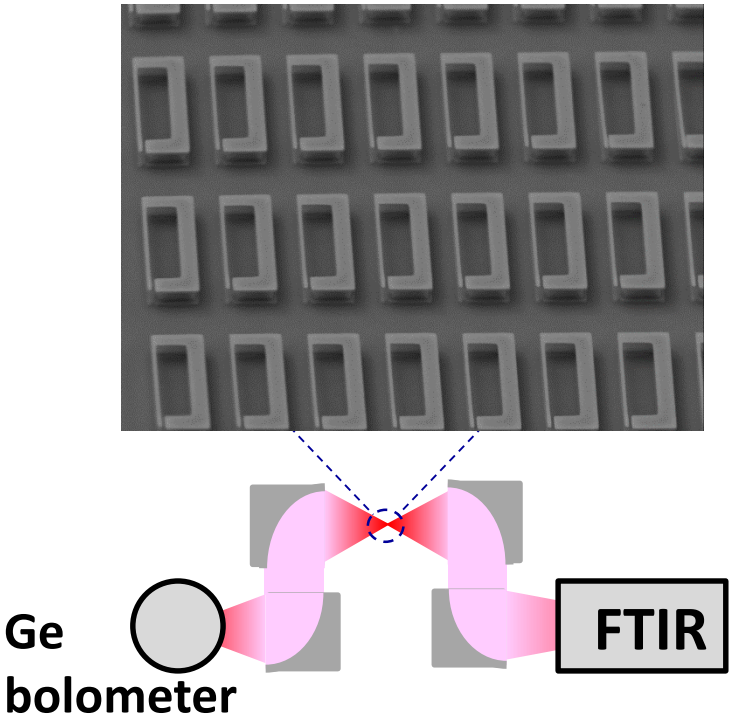


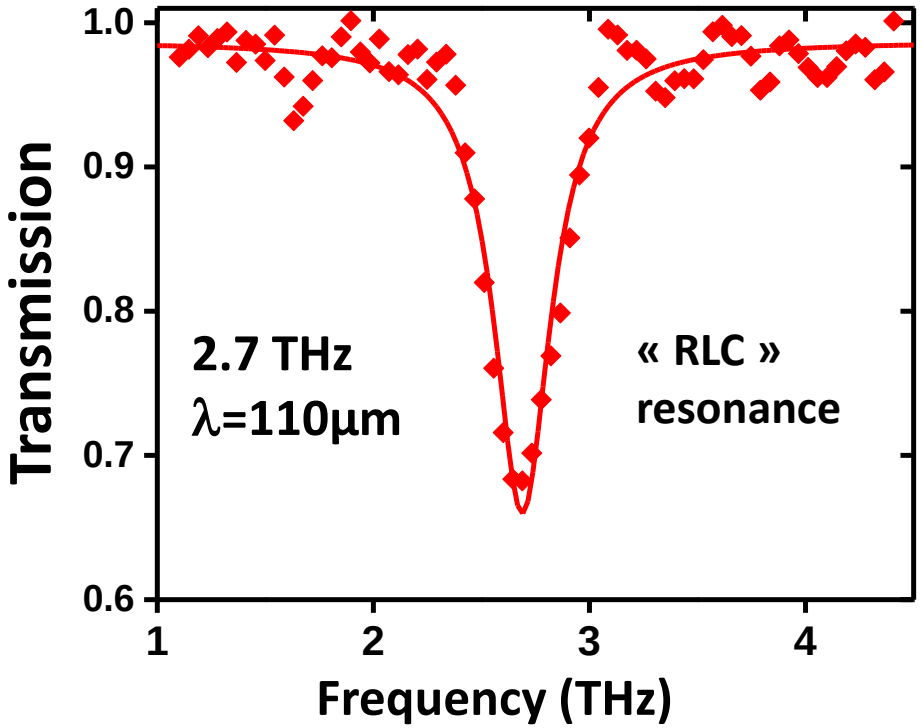




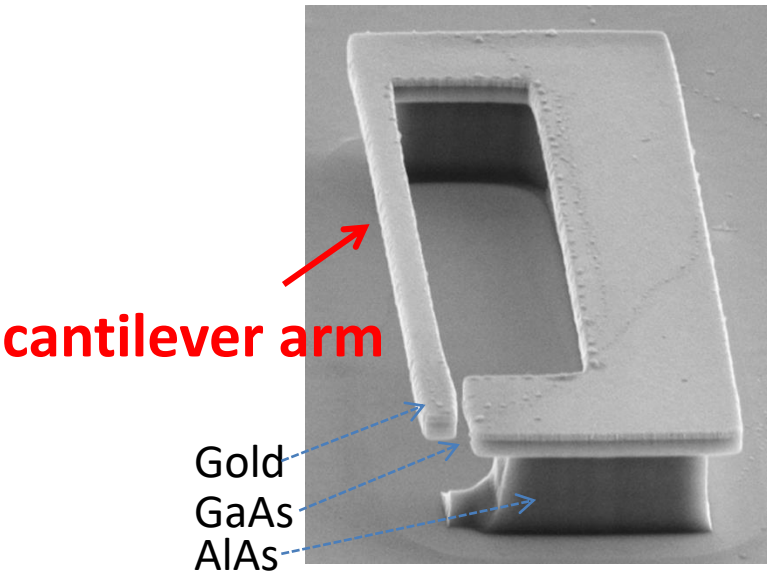
THz optomechanical detector: optical part

Probing in transmission FTIR



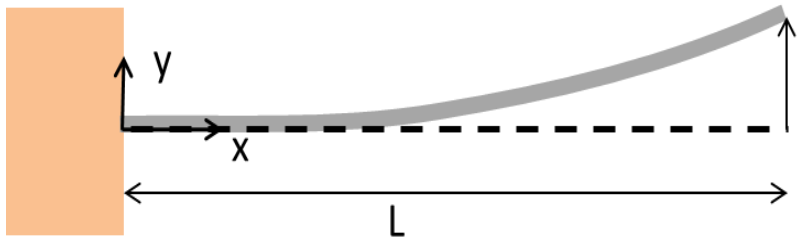


THz optomechanical detector: mechanical part

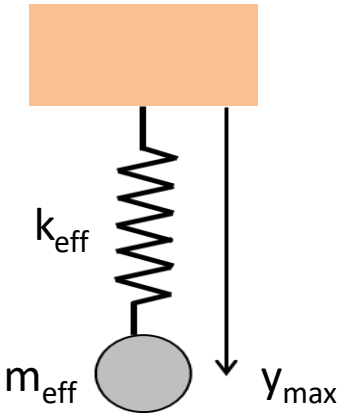


beam (simply clamped, free end)

$y_{max} = y(L)$

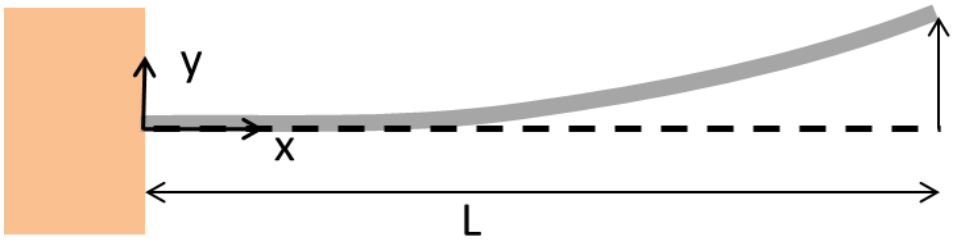


equivalent 1D oscillator



Aspelmeyer,
Rev. Mod. Phys. **86**, 1391 (2014).

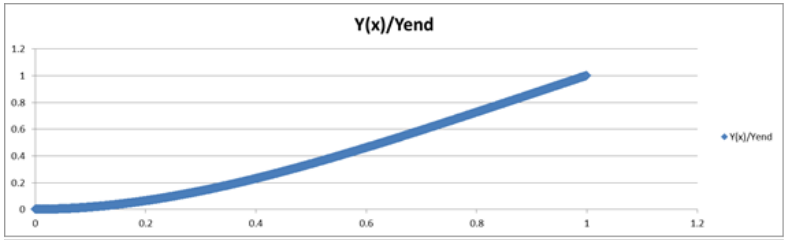
Equation of motion of a cantiliver



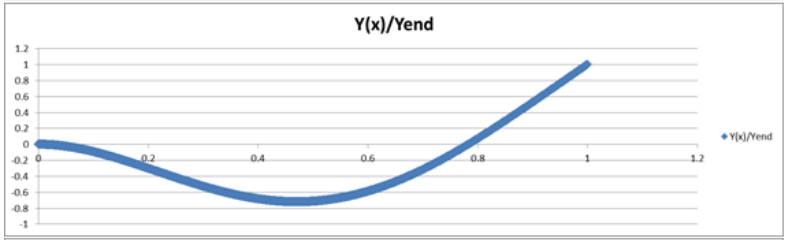
Eigen modes are solutions of the equation:

$$-\mathrm{EI}\frac{\partial^4 y}{\partial x^4} = \rho\frac{\partial^2 y}{\partial t^2}$$

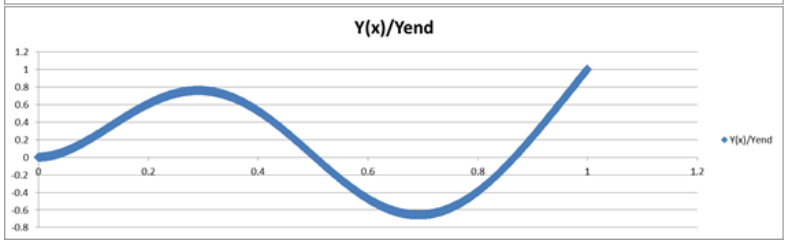
for appropriate boundary conditions.



n=1

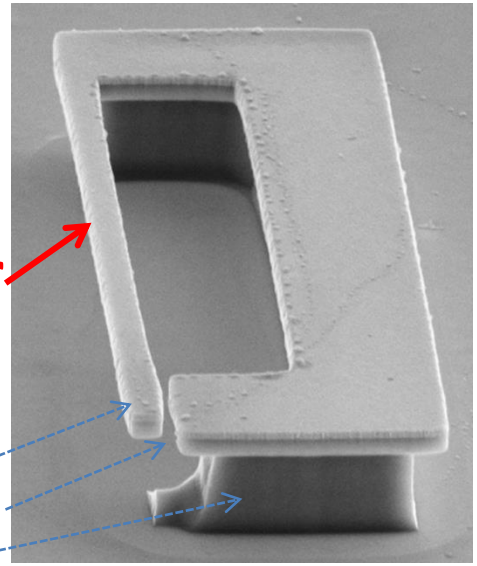


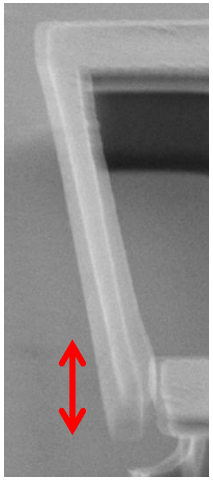
n=2



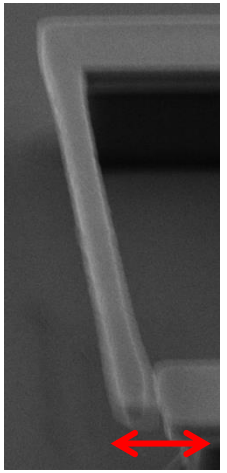
n=3

THz optomechanical detector: mechanical part





955 kHz
out of -plane



1.2 MHz
in-plane

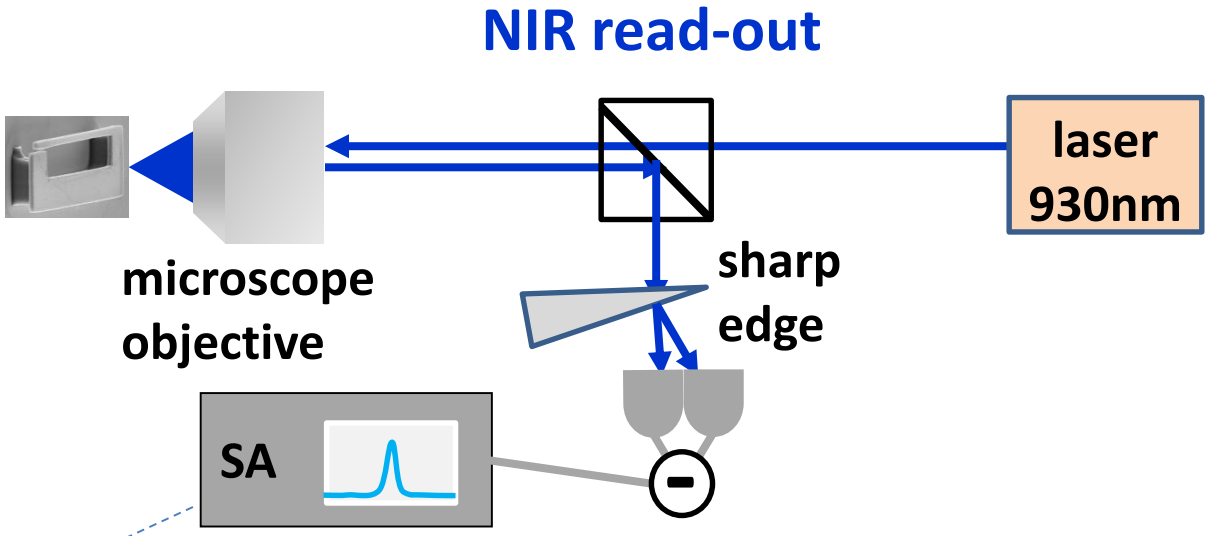
$f_{1\perp}$ ~ height=475nm $f_{1//}$ ~ width=581nm

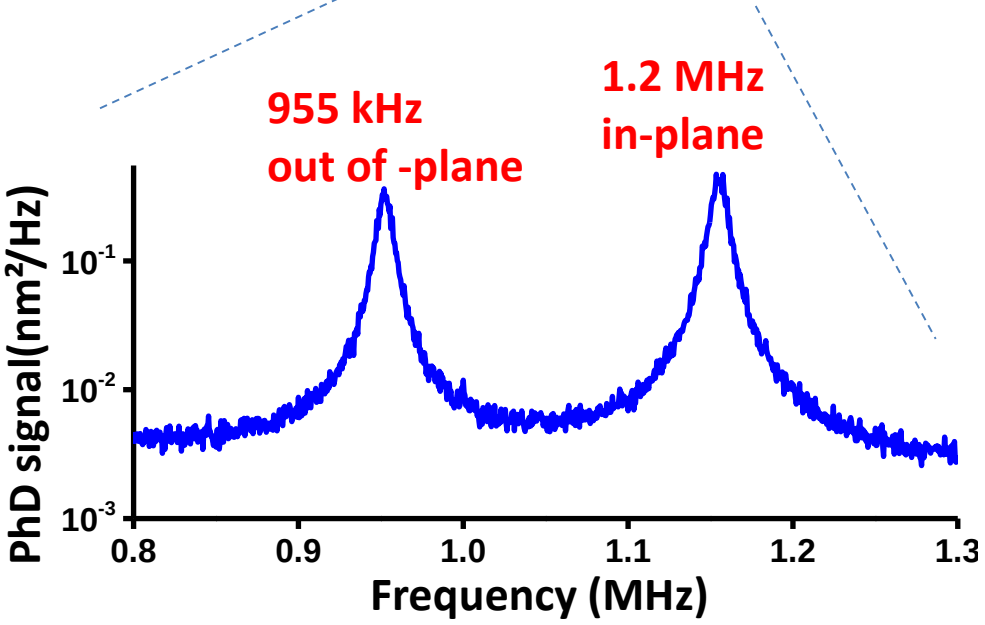
clamped bar:

$$f_1 = 0.162 \frac{w}{L_c^2} \sqrt{\frac{Y}{\rho}}$$

L_c=15μm

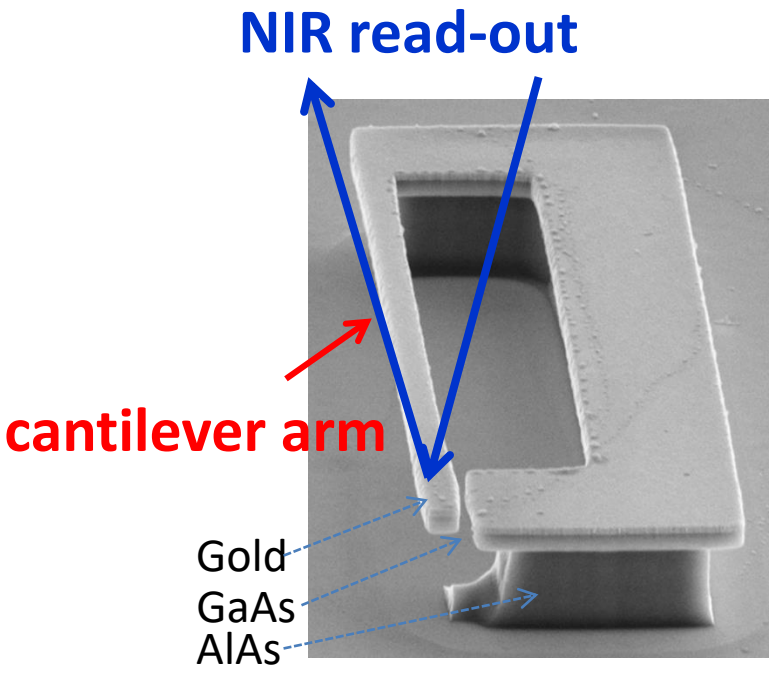
THz optomechanical detector: mechanical part





Brownian motion: thermal noise

THz optomechanical detector: mechanical part

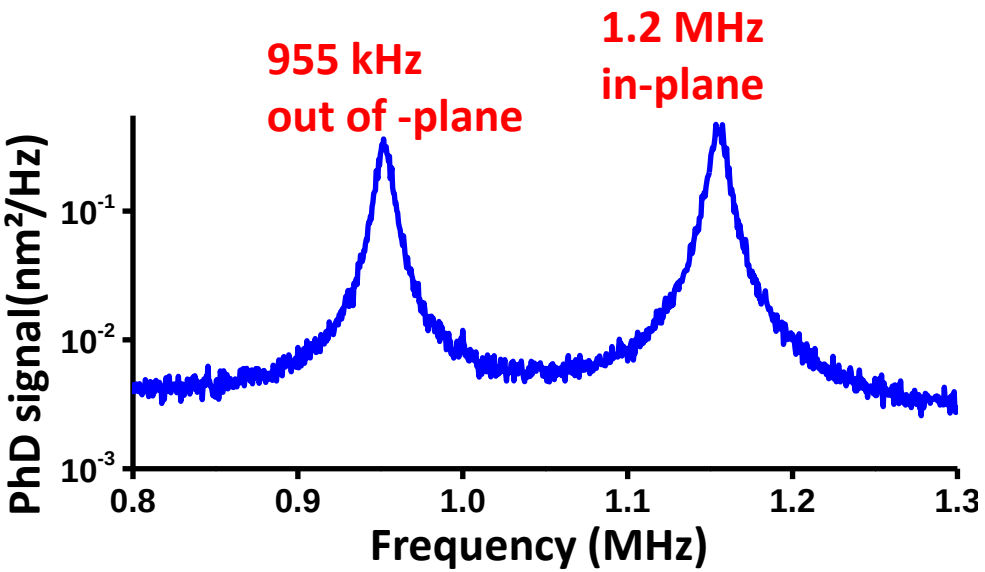


Brownian motion: thermal noise

$$\frac{1}{2} m_{eff} \omega_m{}^2 \langle x^2 \rangle = \frac{1}{2} k_B T$$

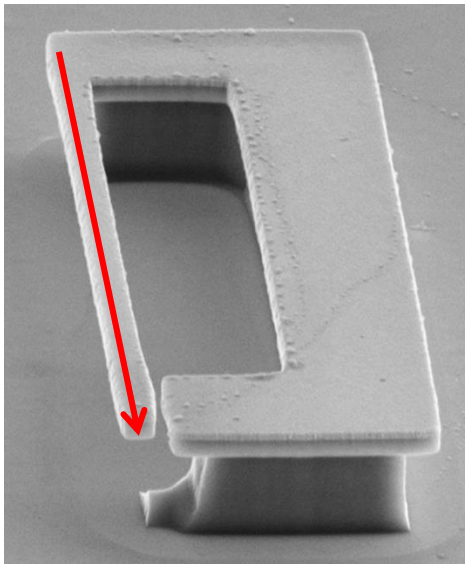
m_{eff} ~ **10pg** → $\sqrt{\langle x^2 \rangle}$ ~ **1 Å**

$S_{xx}(f_m) = 2k_B T Q_m / m_{eff} \omega_m{}^3$ = **0.33pm²/Hz**

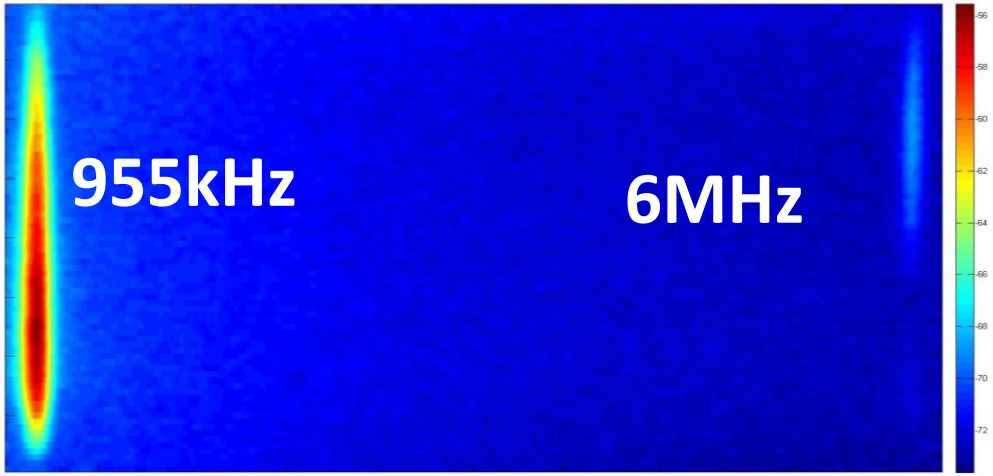


Aspelmeyer,
Rev. Mod. Phys. **86**, 1391 (2014).

High order modes



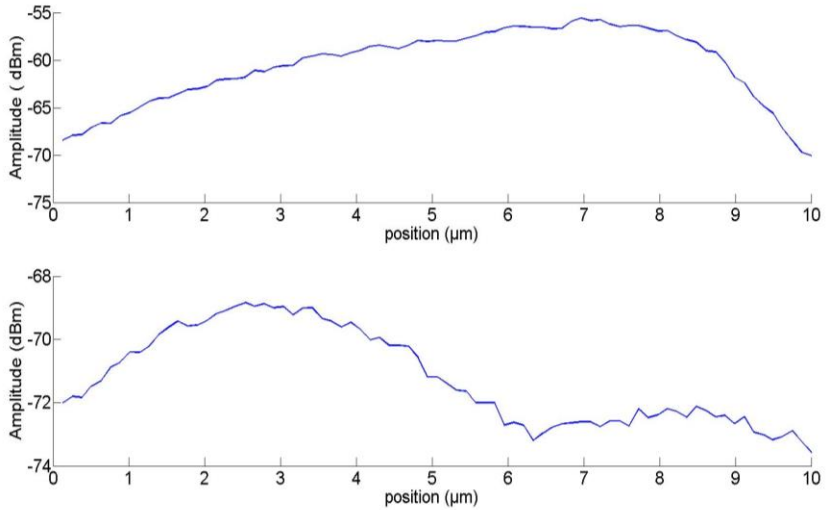
NIR read-out: higher order modes



$$f_n = 2.81 f_1 (n-0.5)^2$$

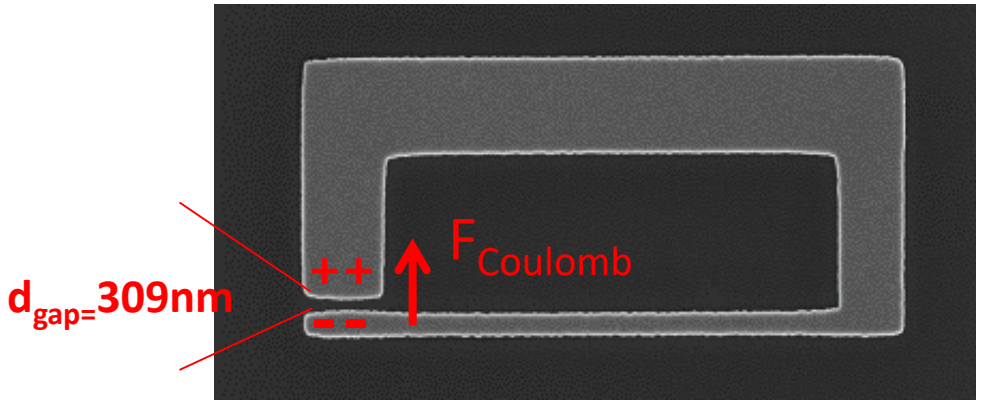
$$\frac{1}{2} m_{eff} \omega_m{}^2 \langle x^2 \rangle = \frac{1}{2} k_B T = const!$$

m_{eff} = 10 pg = *const*



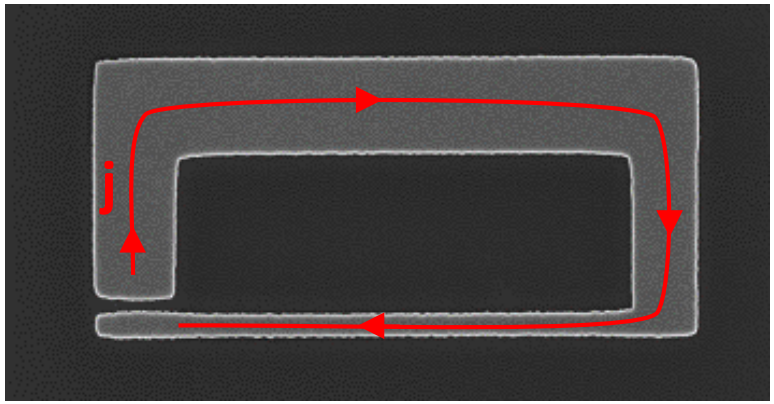
What kind of physical effects of the THz waves we can expect on this structure?

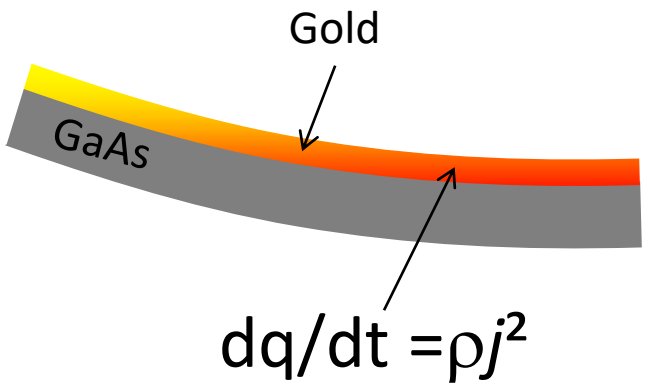
a. Electro-mechanical interaction: Coulomb force.



$$F_{Coulomb} = -W_{THz} \left. \frac{d \ln C_{eff}}{dx} \right|_{x=d_{gap}}$$

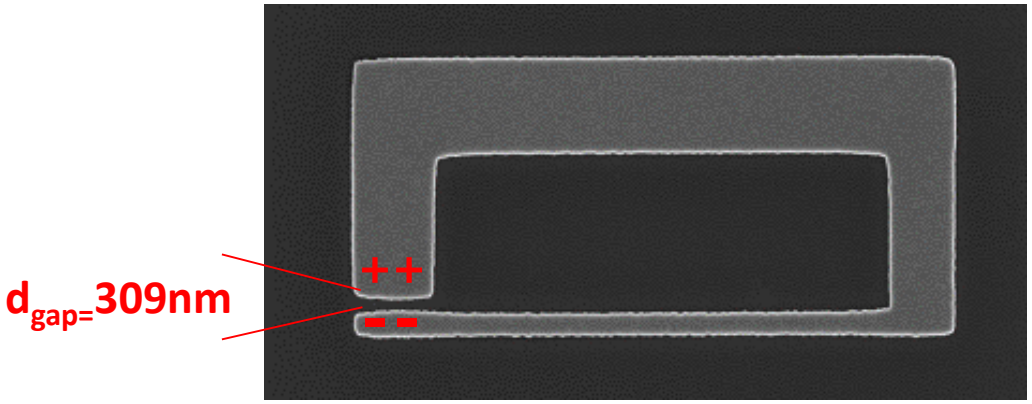
b. Photo-thermal (bolometric) interaction.

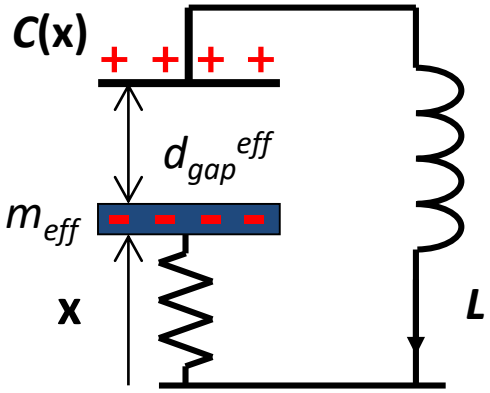




Electro-mechanical interaction: Coulomb force

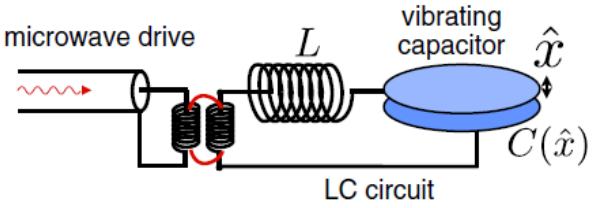
non-bolometric force





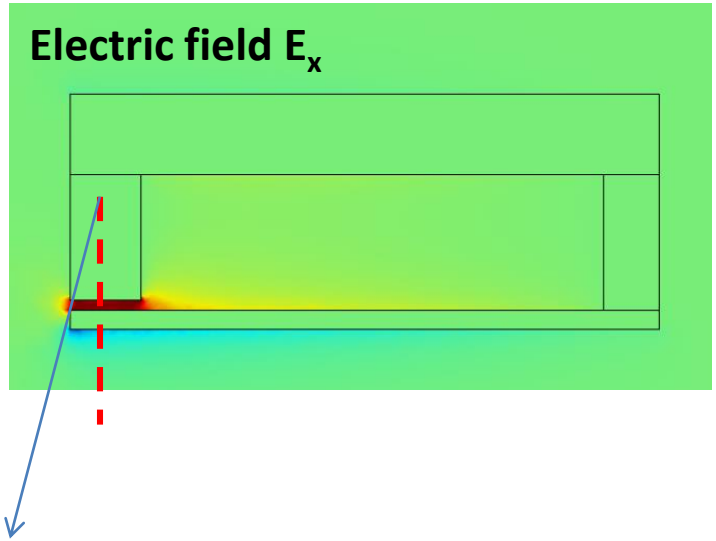
$$\frac{d^2x}{dt^2} + \frac{\omega_m}{Q_m}\frac{dx}{dt} + \omega_m^2 x = -\frac{W_{THz}(t)}{m_{eff}}\frac{d\ln C_{eff}}{dx}\bigg|_{x=d_{gap}}$$

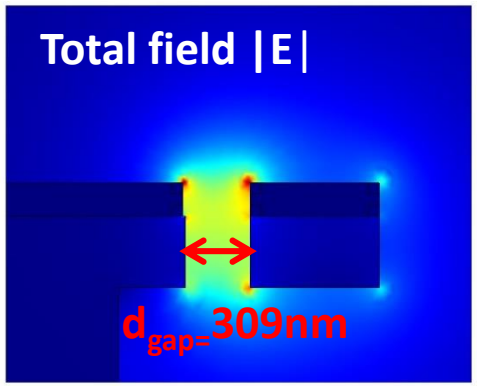
Stored electric THz energy



Bagci, T., *et al.* , *Nature* **507**, 81–85 (2014)

Electro-mechanical interaction: Coulomb force: « non-bolometric »





$$d_{gap}^{eff} = \left(\frac{d \ln C_{eff}}{dx}\bigg|_{x=d_{gap}} \right)^{-1}$$

d_{gap}^{eff} = 800nm

THz force for 1nW of coupled power:

$$W_e = \frac{1}{2} P Q_{THz}/\omega_{THz} \sim 1.8\text{x}10^{-22}\ \text{J}$$

$$F_{\text{Coulomb}} = W_e / d_{gap}^{eff} = 0.2\ f\text{N}$$

Stiffness: $k = m_{eff}\omega_m^2 = 0.4\text{N/m}$

$$x = F_{\text{Coulomb}}/k = 0.5\text{fm} \ldots$$

… But if the oscillator is resonantly driven with Q_m=100:

$$x_{max} = Q_m F_{THz}/k = 50\ \text{fm}$$

Electro-mechanical interaction: Coulomb force: « non-bolometric »

Figures of merit

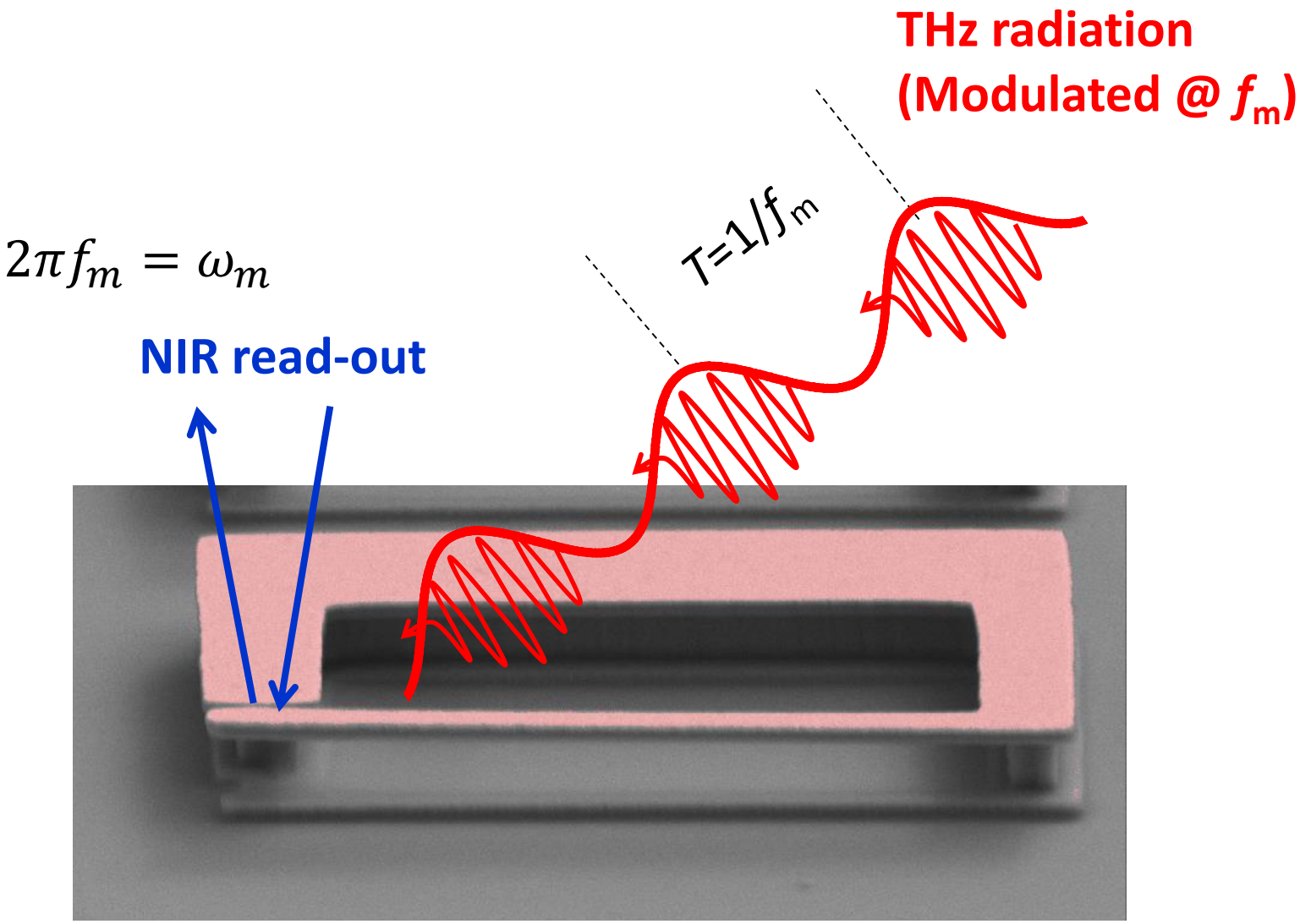
$$R_{in} = \frac{x_{\max}}{P_{THz}} = \frac{Q_m}{2m_{eff}\omega_m^2}\frac{Q_{THz}}{d_{gap}^{eff}\omega_{THz}}$$ **~ 50 fm/nW**

$$NEP = \frac{\sqrt{S_{xx}(\omega_m)}}{R_{in}} = \sqrt{2k_B T m_{eff}\frac{\omega_m}{Q_m}}\frac{2\omega_{THz}d_{gap}^{eff}}{Q_{THz}}$$ **~ 10 nW/Hz$^{0.5}$**

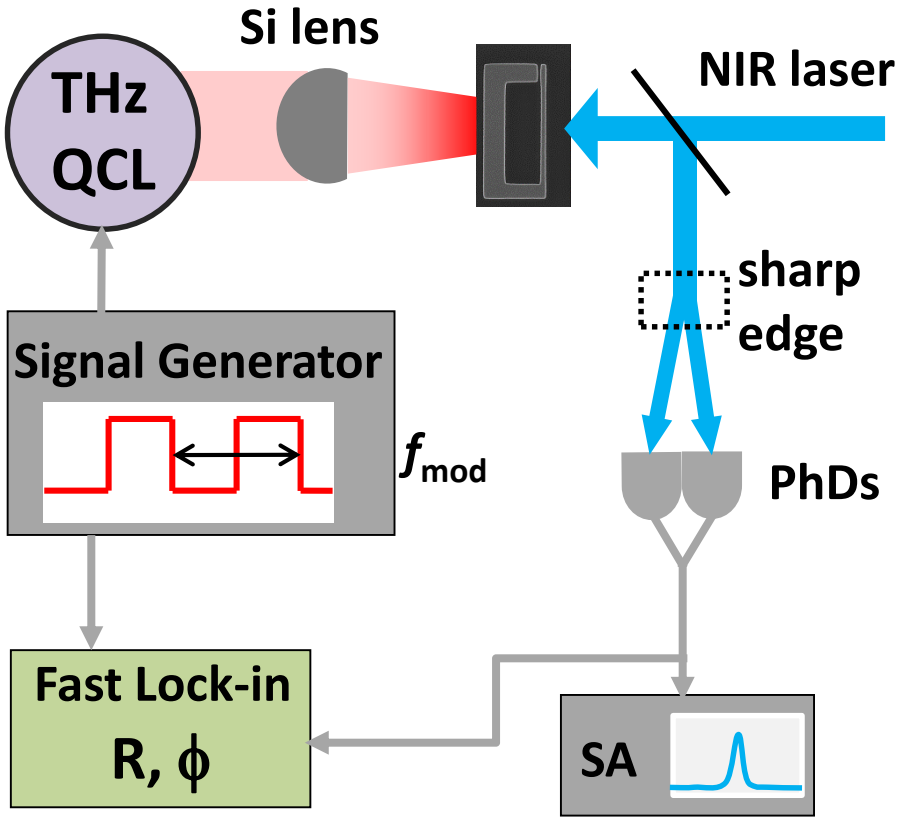
@ 1 MHz and higher

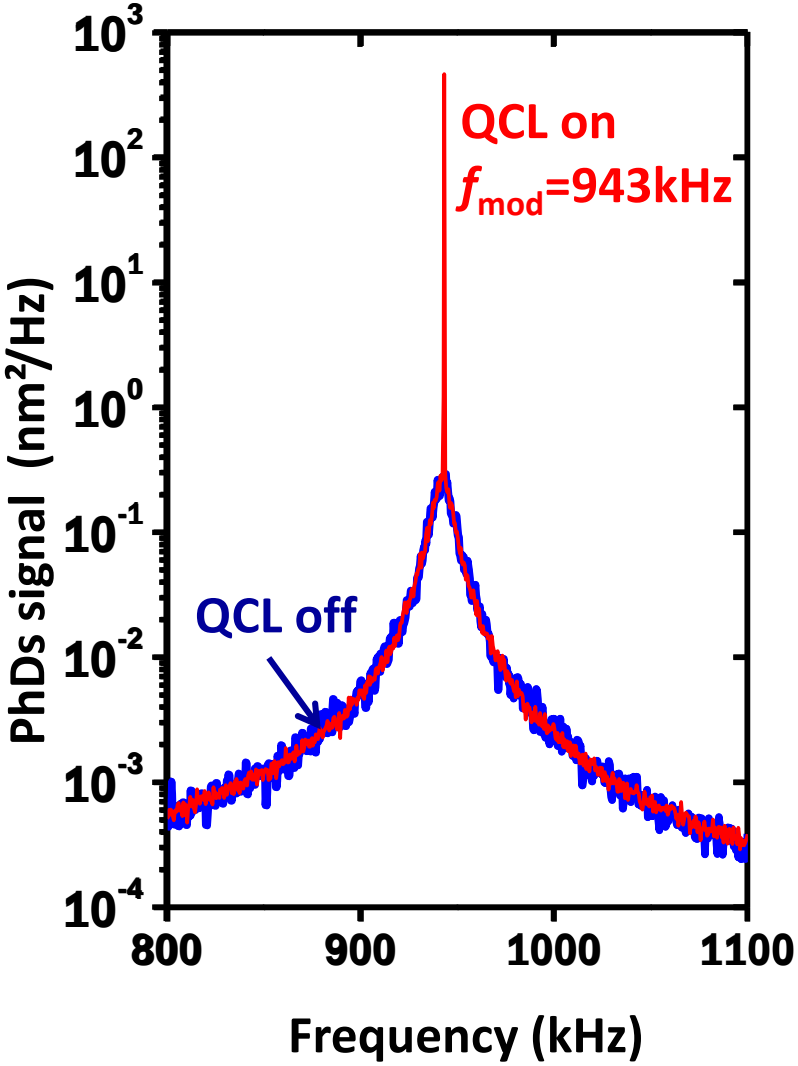
THz detection

Principle of operation

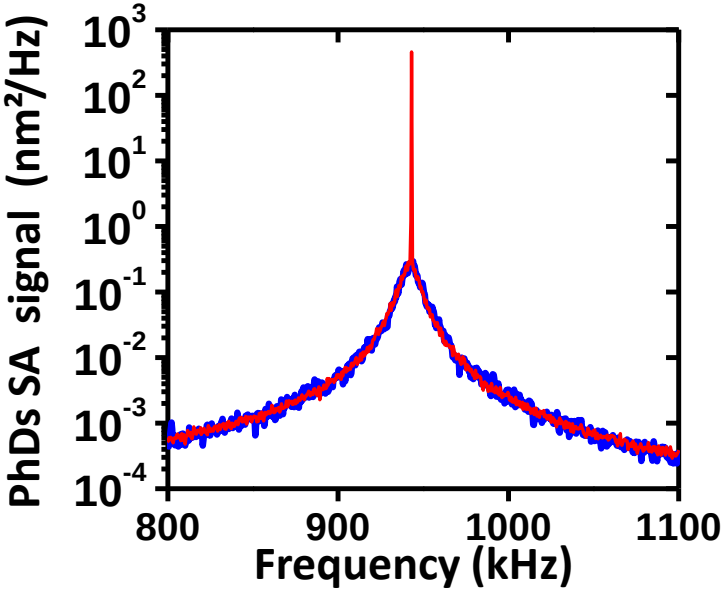


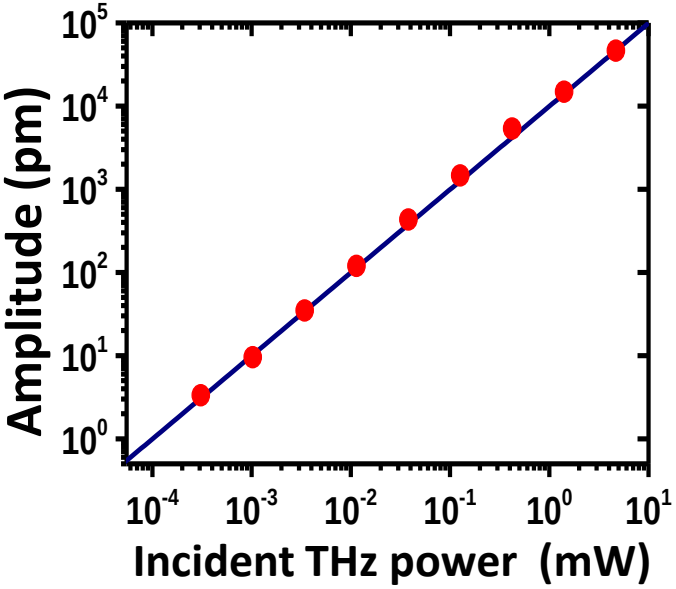
THz optomechanical signal





Performance as a detector

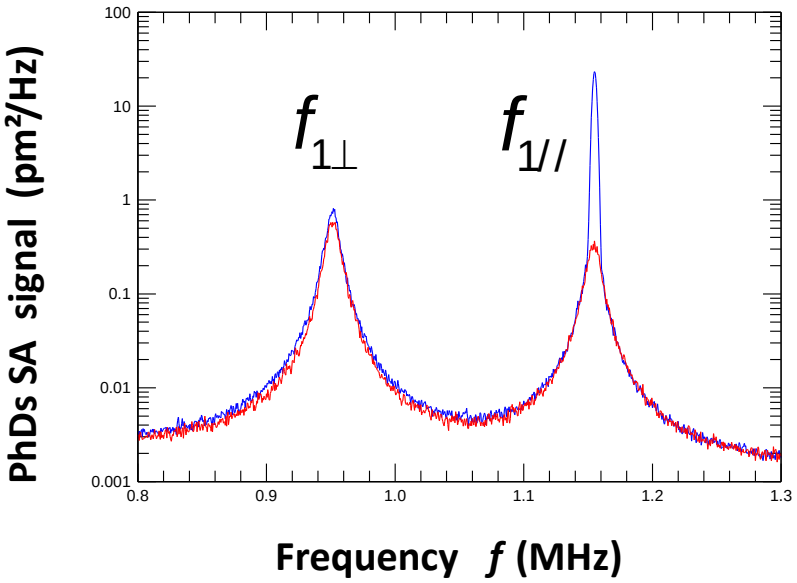


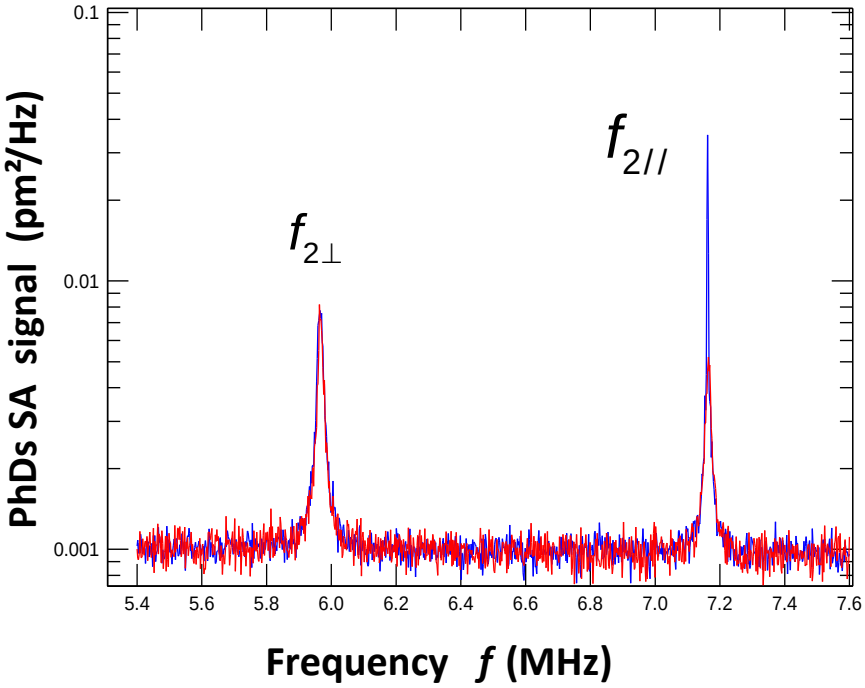


Brownian motion limited NEP: **8 nW/Hz$^{1/2}$**

Performance as a detector

Electro-mechanical mechanism





R_{exp} ~ 5 fm/nW

NEP_{exp} ~ 80 nW/Hz$^{0.5}$

NEP_{exp} ~ 90 nW/Hz$^{0.5}$

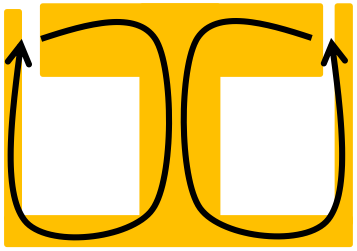
Going further?

$$NEP = \sqrt{2k_B T m_{eff}} \frac{\omega_m}{Q_m} \frac{2\omega_{THz} d_{gap}^{eff}}{Q_{THz}}$$

More symetry to decrease radiation loss

In air: Q_m**~70**

In vacuum: Q_m**~2000**



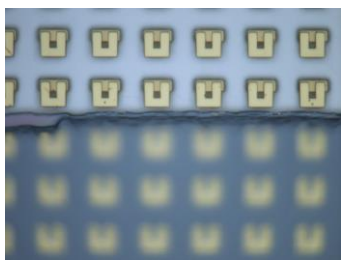
Q_{THZ}**~100**

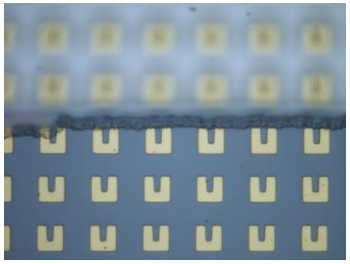
Al-Naib, et al.
Appl. Phys. Lett. **106**, 011102 (2015)

NEP <100pW/Hz$^{0.5}$ is within reach

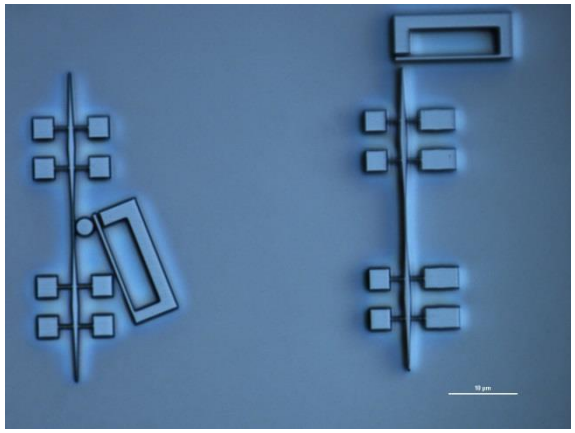
Conclusion & Perspectives

I. THz metamaterial resonators have strong potential for improving the temperature operation of quantum detectors





II. Towards compact THz optomechanical metamaterial sensors



Opto-mechanical interaction within *single* sub-wavelength resonator

« Material free concept » OK for Si

Scanning the modulation frequency

1st order

2nd order

3rd order