THE NATO science for Peace and Security Programme

THESEUS
Terahertz sources for Humans and Environmental SEcUrity

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Nanomaterials and microstructures for THz devices

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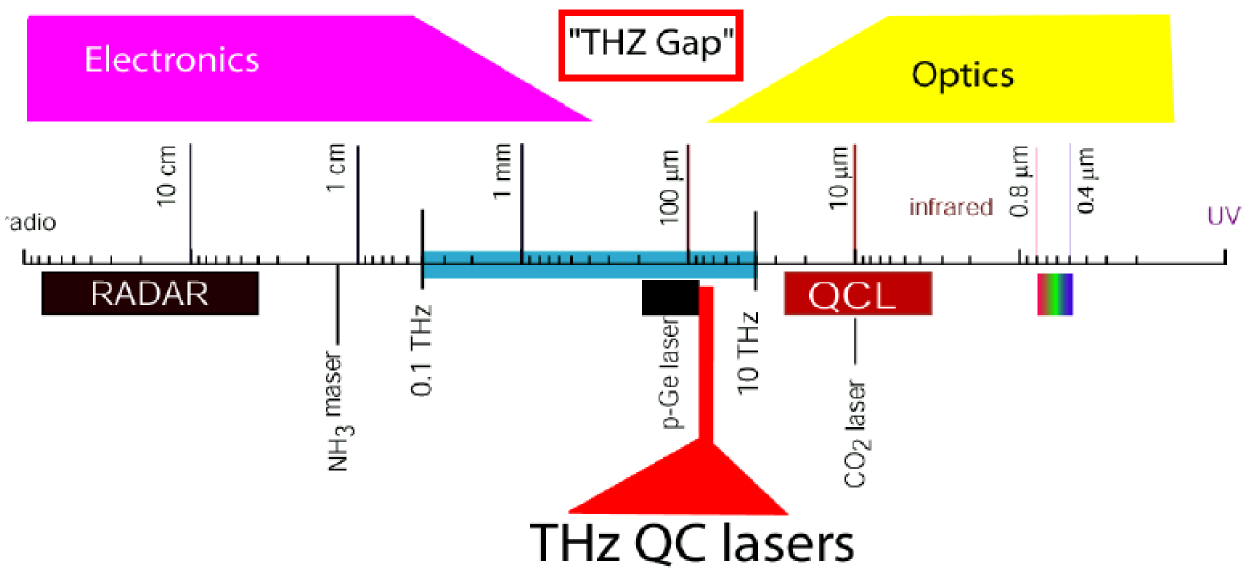
Università di Pisa

THz: what and why

1 THz =	300cm^{-1} =	4.1meV =	300μm
Frequency	Energy (cm^{-1})	Energy (meV)	Wavelength



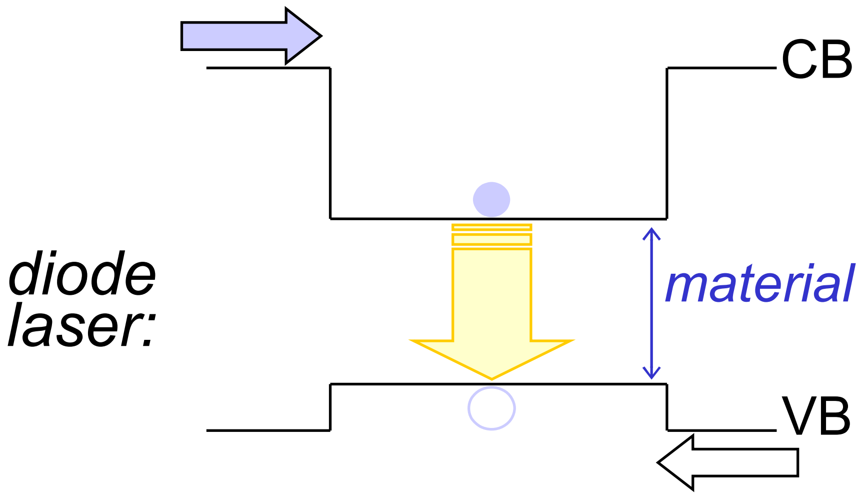
Applications

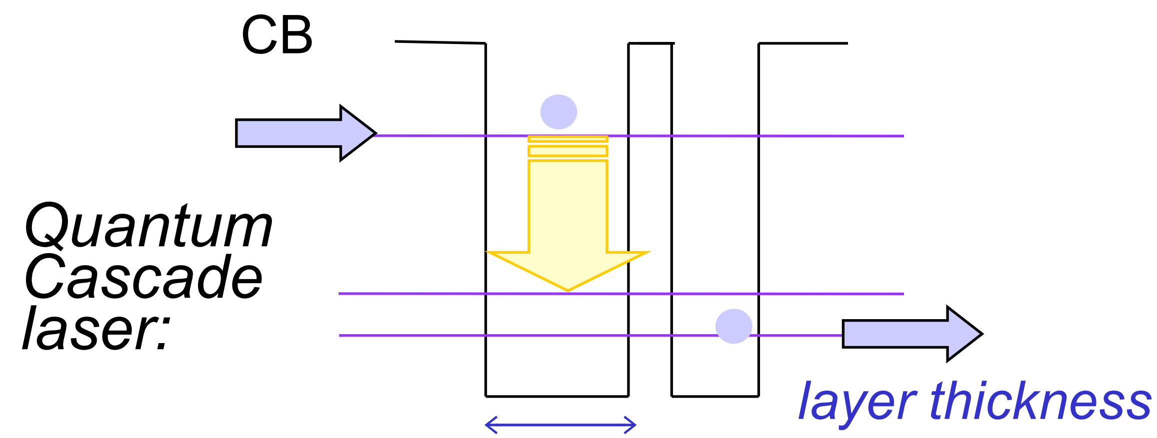
- Information and communication technology
  - Wireless communications
- Space Science
- Environment
  - Atmospheric sensing
- Medicine
  - Imaging of biological tissue
- Security Controls
- Defense
  - Chemical agent detection
  - Transportation
- Material processing
  - Tomography

Improve the functionality of the systems to address application requirements

- Compact and efficient **THz sources**:
  - High temperature, high power, wide tunability, ultra-narrow
  - Regular and low divergent beam profiles
- High speed, high dynamic range **THz detectors**

The unipolar semiconductor laser





"materials by design":
band structure engineering and molecular beam epitaxy (MBE)
population inversion, matrix elements, scattering times, and transport are *designed* for optimum performance

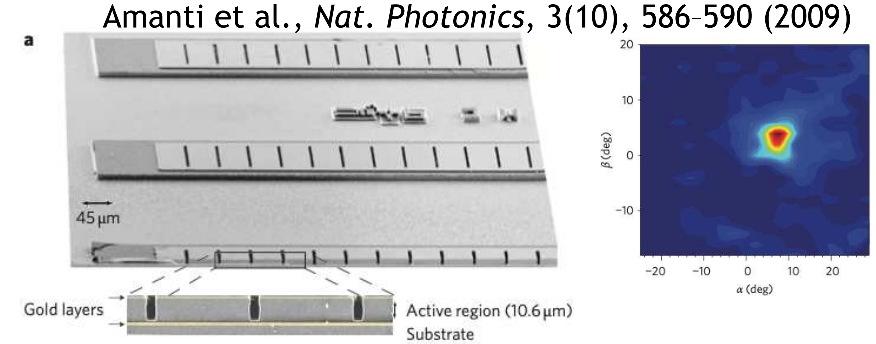
- 1971: amplification from intersubband transitions is first postulated by R. F. Kazarinov and R. A. Suris *Sov. Phys. Semicond.* ***5**, 207* *(Ioffe)*
- 1994: QC-laser is first experimentally demonstrated by J. Faist et al. *Science* ***264**, 553* *(Bell Labs)*

THz QCLs

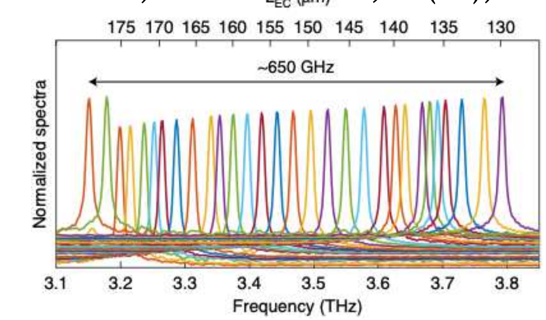
Excellent performance in terms of:

- high emitted power (> 1 W in pulse mode, 0.23 W in CW)
- stable single mode or broadband operation
- large frequency tunability (up to 0.65 THz)
- low divergence (a few degrees) and good beam quality of emission

Amanti et al., *Nat. Photonics*, 3(10), 586-590 (2009)



C. A. Curwen et al., *Nat. Photonics*, 13(12), 855-859 (2019)



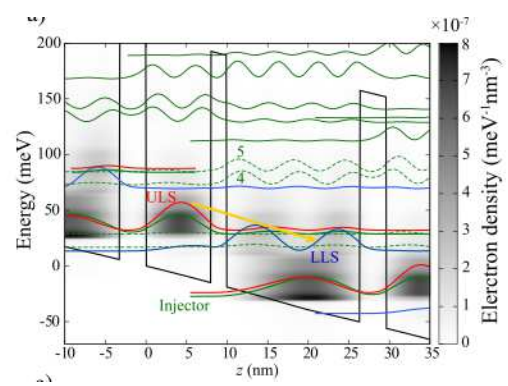
However, there are still open challenges:

Room temperature operation

actual record 250 K,

Khalatpour et al., Nat. Photonics 15(1), 16-20, (2021)

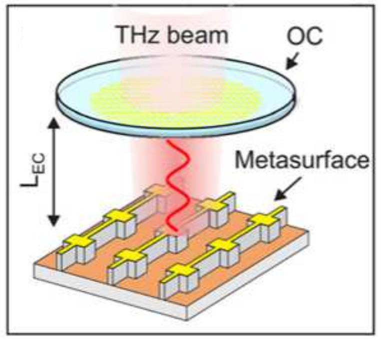
TE-cooled



L. Bosco et al., Appl. Phys. Lett. 115, 010601 (2019)

Active region design optimization

Efficient CW emission



Low power consumption

High power efficiency

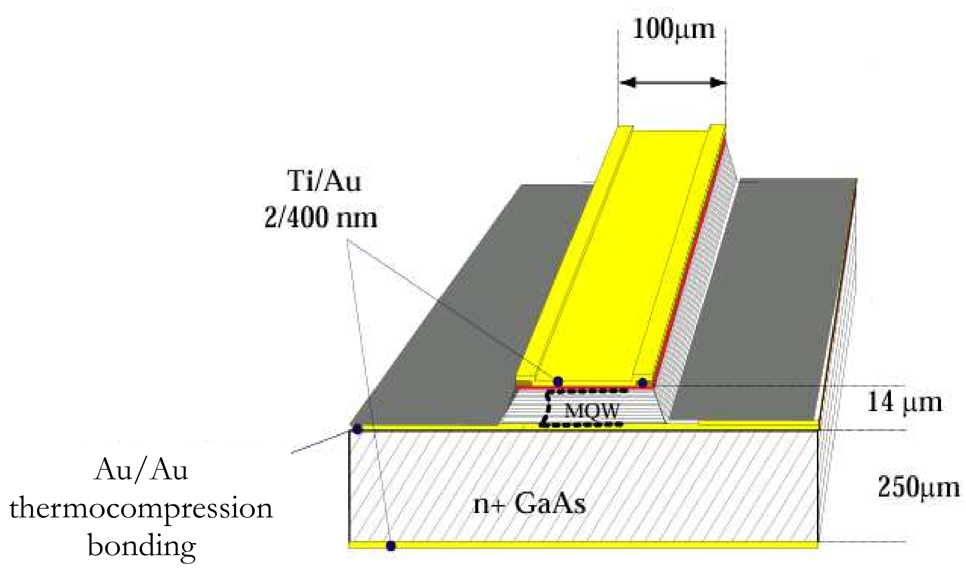
C. A. Curwen et al., Appl. Phys. Lett. 116, 241103 (2020)

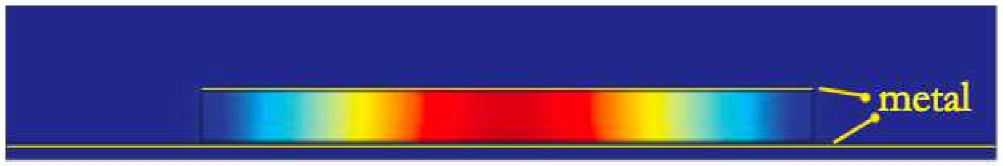
Cavity engineering

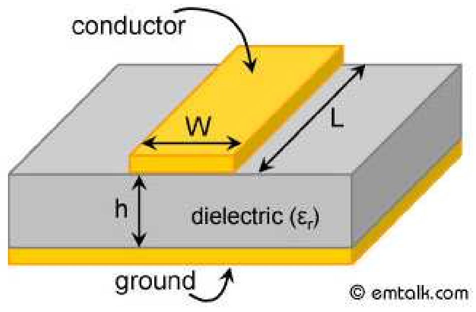
miniaturization?

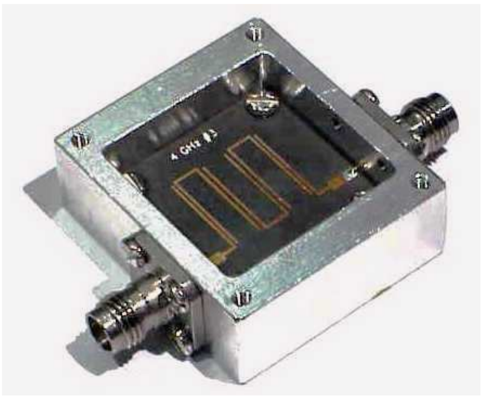
THZ QCLs waveguide

- Use a microstrip geometry
  - broadband, high mirror reflectivity, good injection



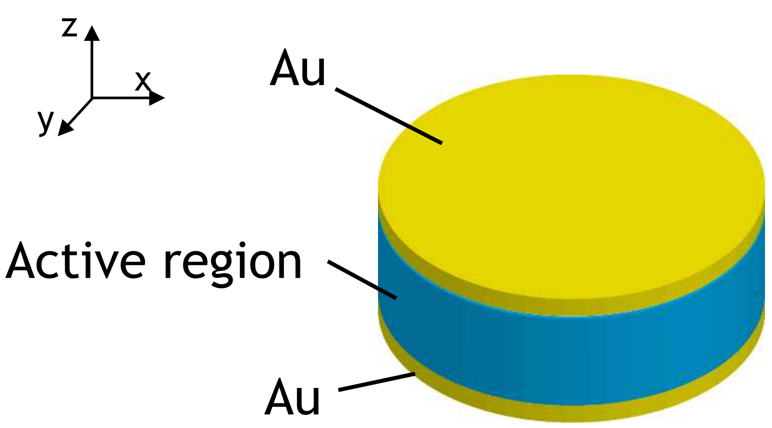






THz QCL microcavities

The whispering gallery resonator



Lateral confinement: total internal reflection

Whispering Gallery Modes (WGM)

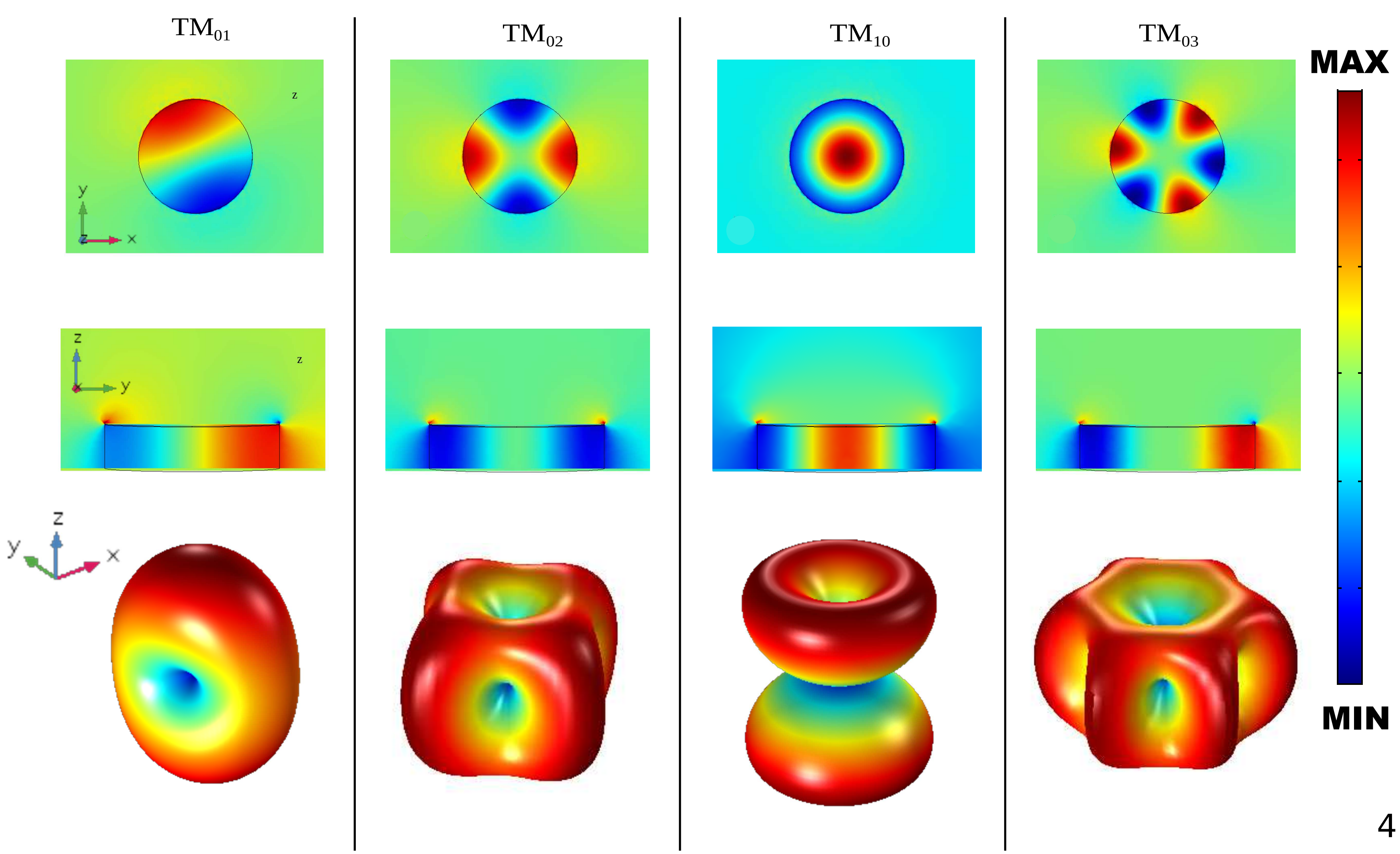
lateral sub-wavelength circular dimension

high Q-factor

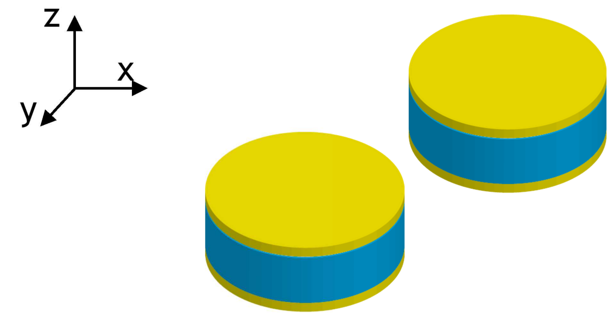
Vertical confinement:
double-metal waveguide
E-field totally confined in the AR
one TM mode always confined

Advantages:
Sub-wavelength mode volumes
mA threshold current

Drawbacks:
divergent isotropic
low outpu

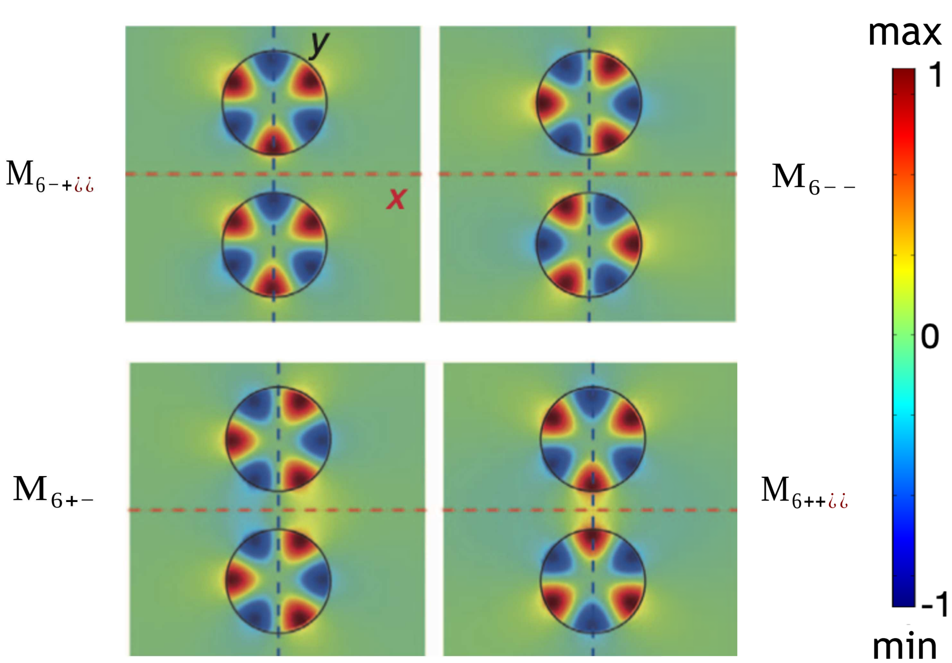


The dipole-antenna microcavity



Supermodes by cavity coupling

M_{2} ±±

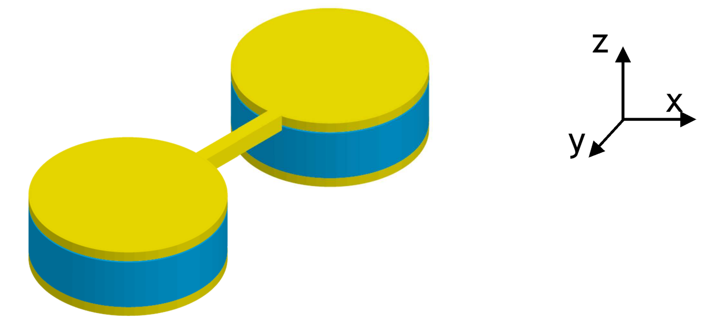


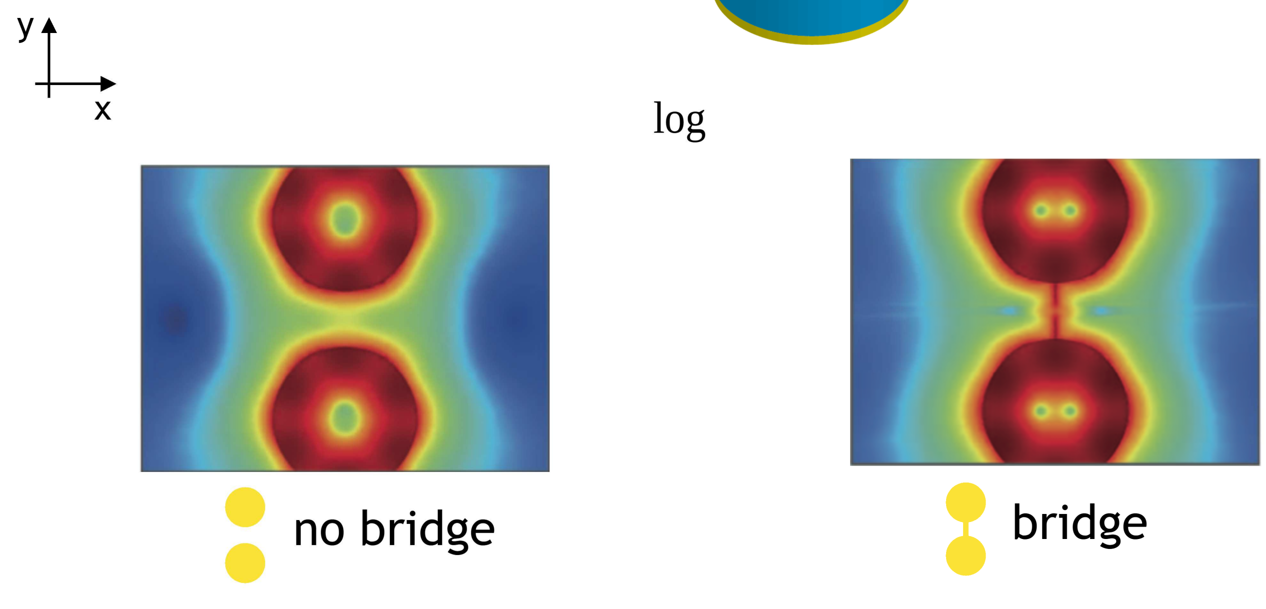
2n: number of E-field antinodes

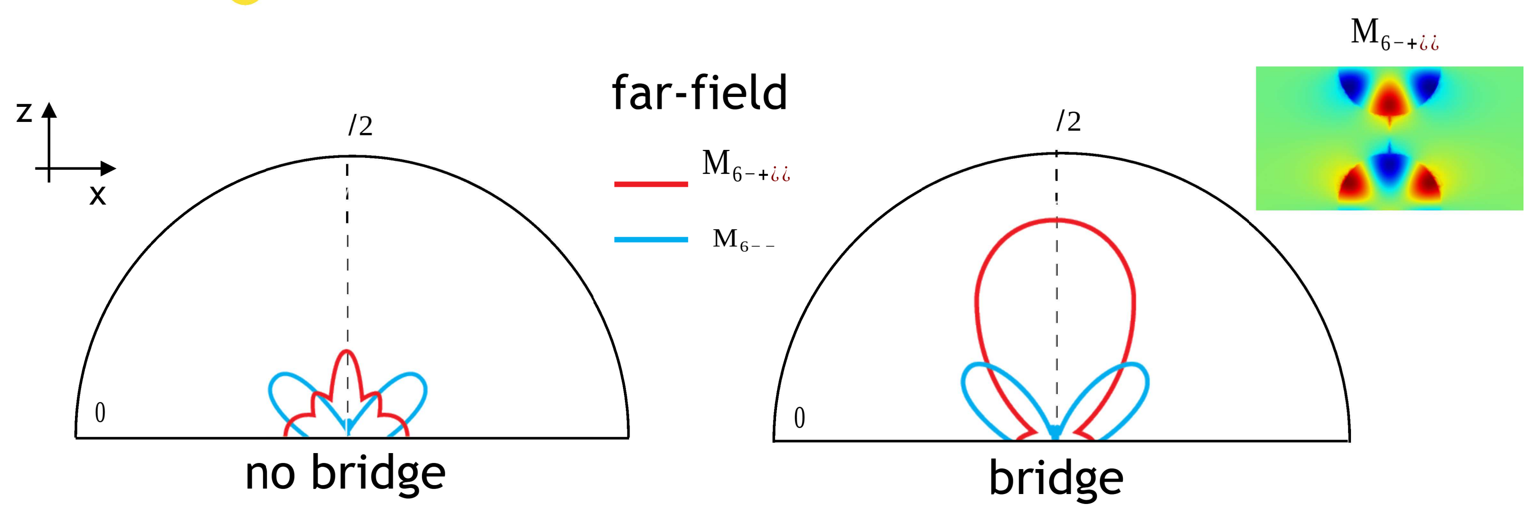
first ± : e/o symmetry with respect to x

second ± : e/o symmetry with respect to y

Adding a suspended gold bridge







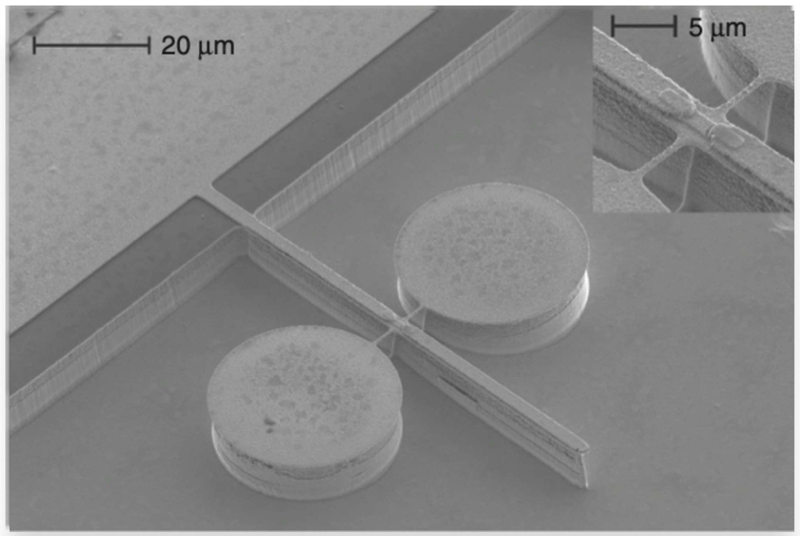
radial spread emission

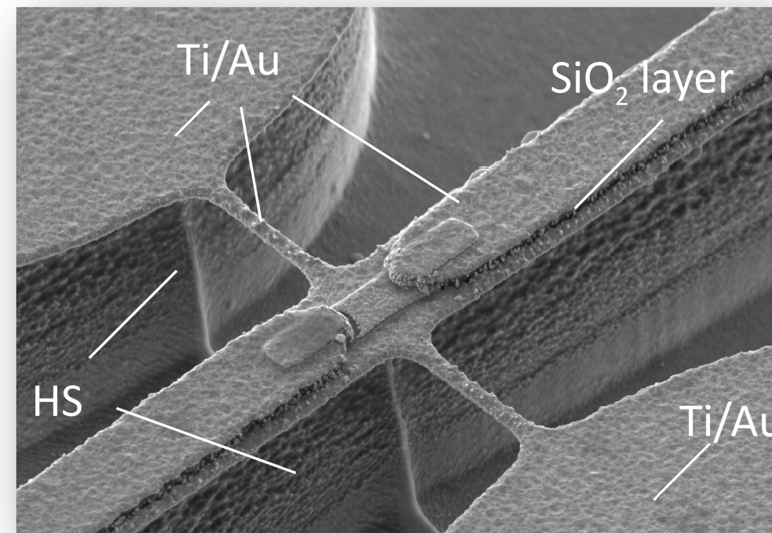
dipole-antenna emission:
dipole-like E-field distribution

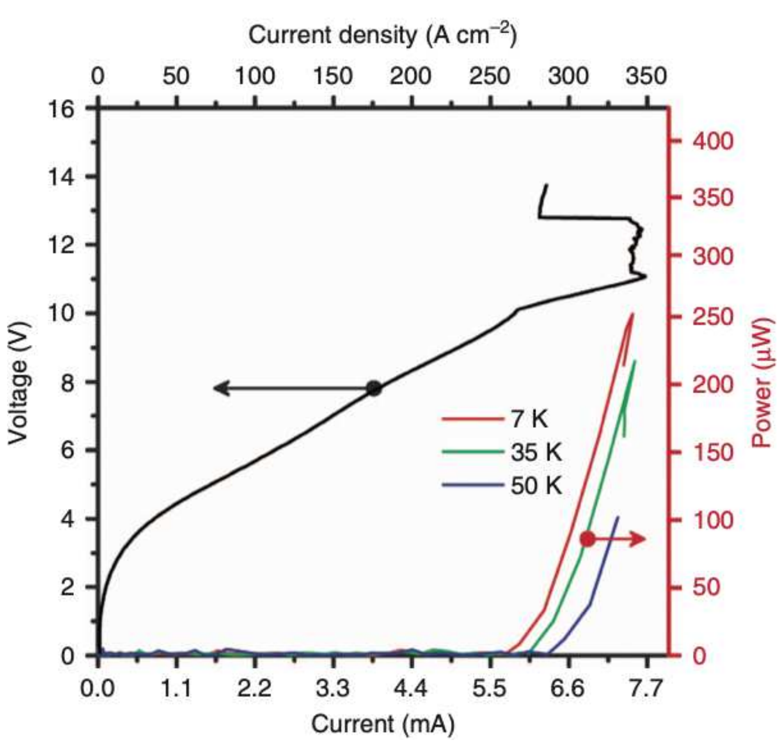
Vertical emission: integration

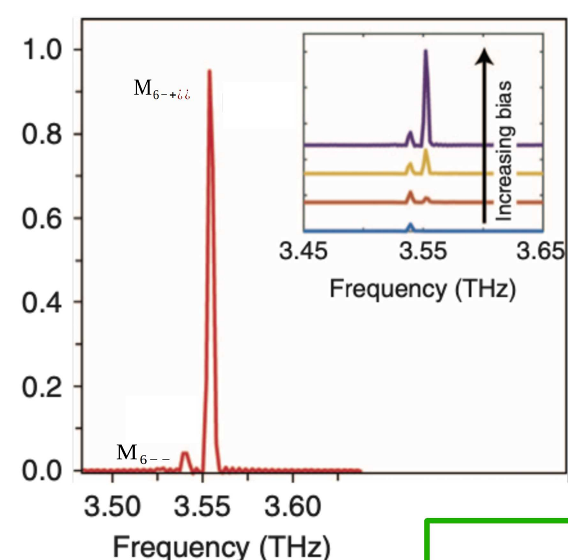
The dipole-antenna microcavity

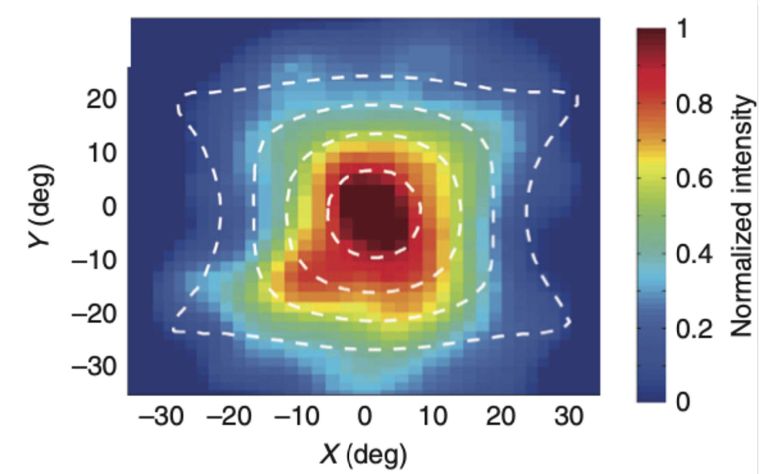
Continuous wave laser operation of a dipole-antenna terahertz microresonator,
L. Masini et al., *Light: Science & Applications*, *6*, e17054 (2017)









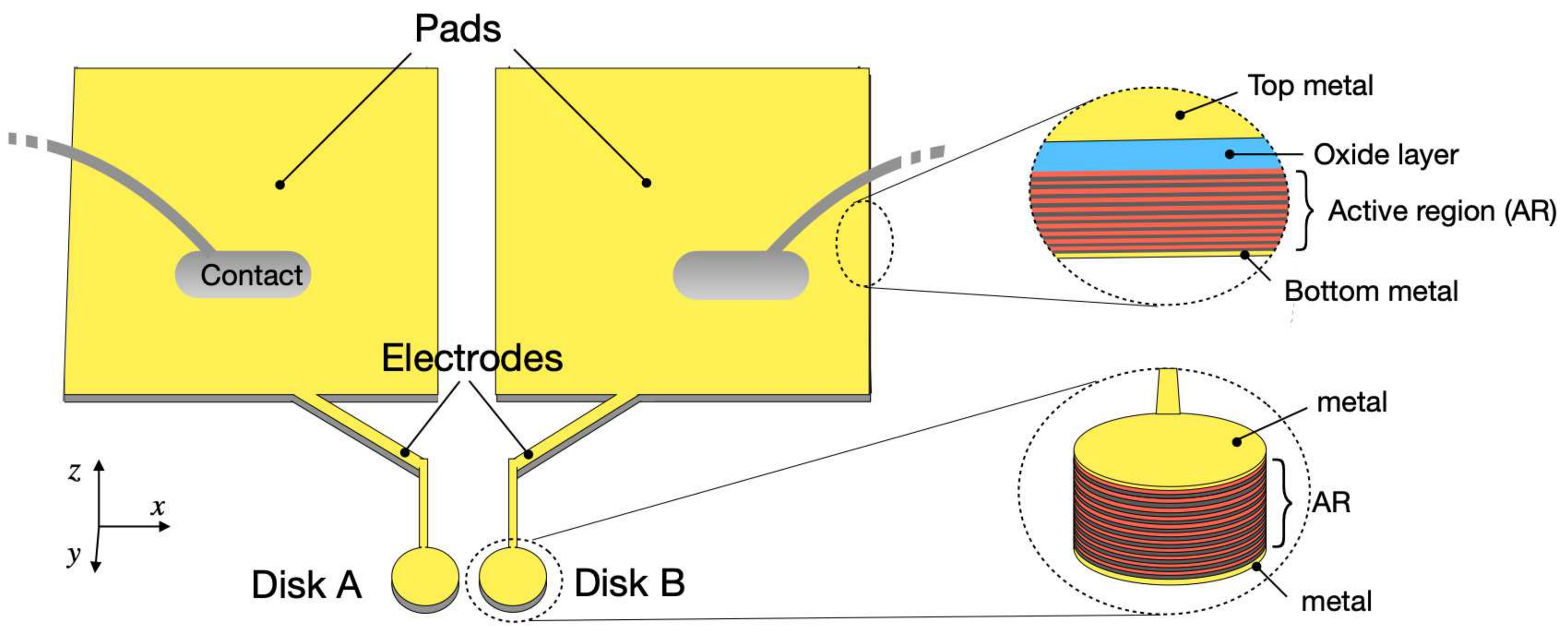


< 6 mA threshold, CW operation
~ 250 µW emitted power
~ 160 mW/A power efficiency
vertical, 10°- collimated emission

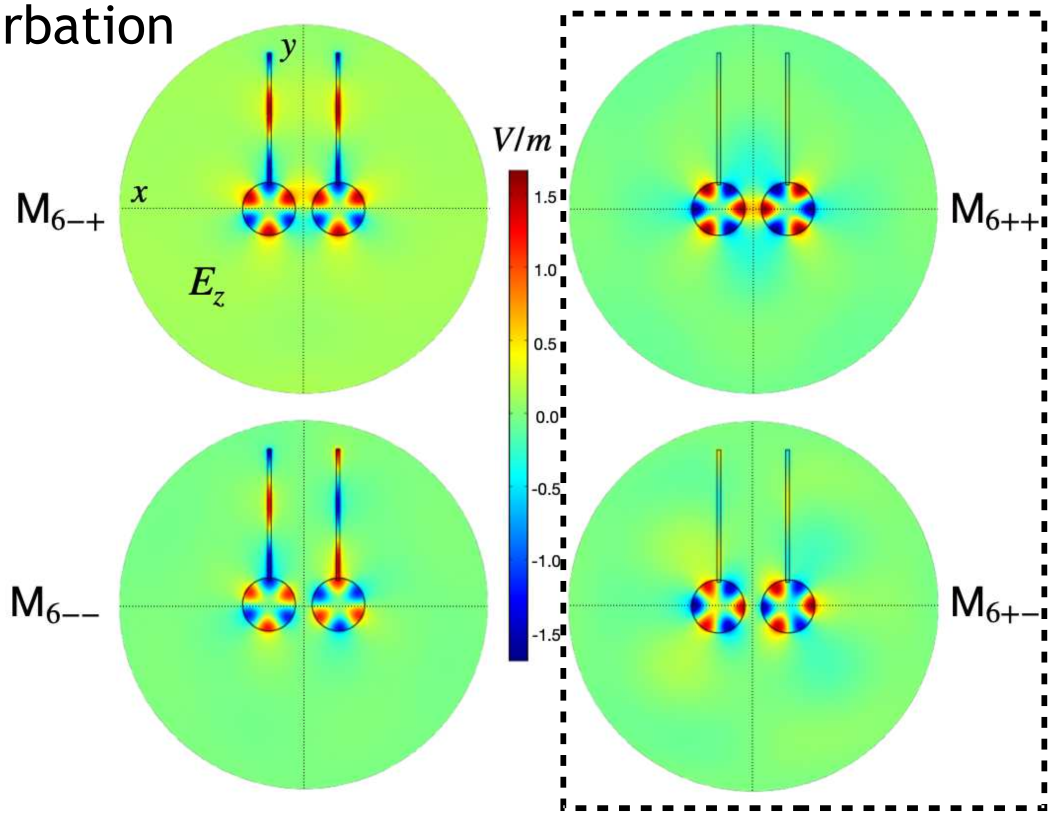
Dual-injection scheme

M. Brandstetter, et al.," Nat. Commun. 5, 4034–4037 (201

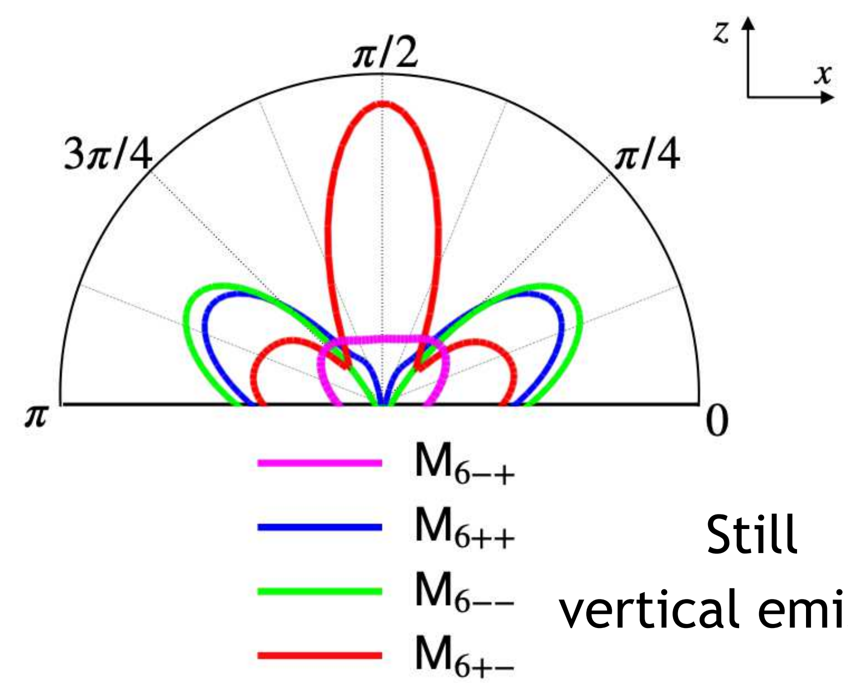
Each microresonator can be independently pumped:



No modes perturbation



Out-coupling fixed by geometry



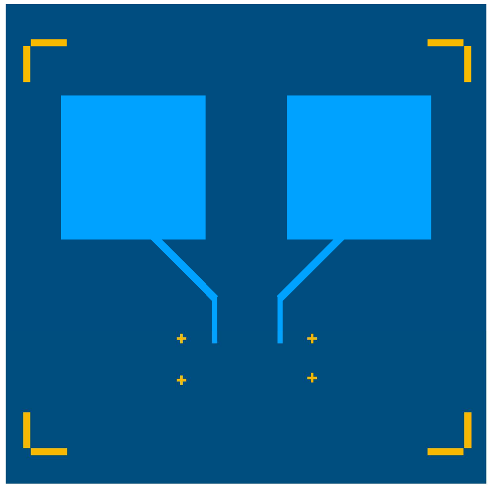
Still vertical emission

Fabrication process

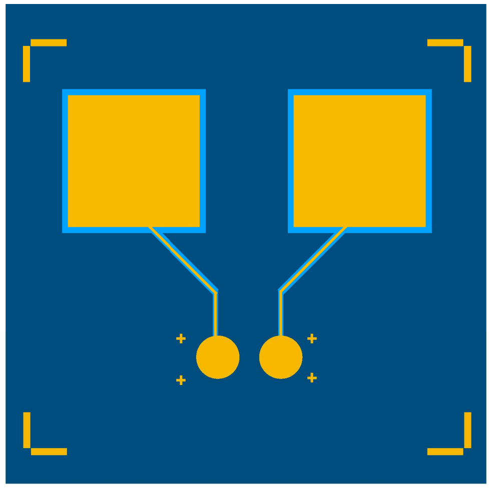
1. EBL of markers

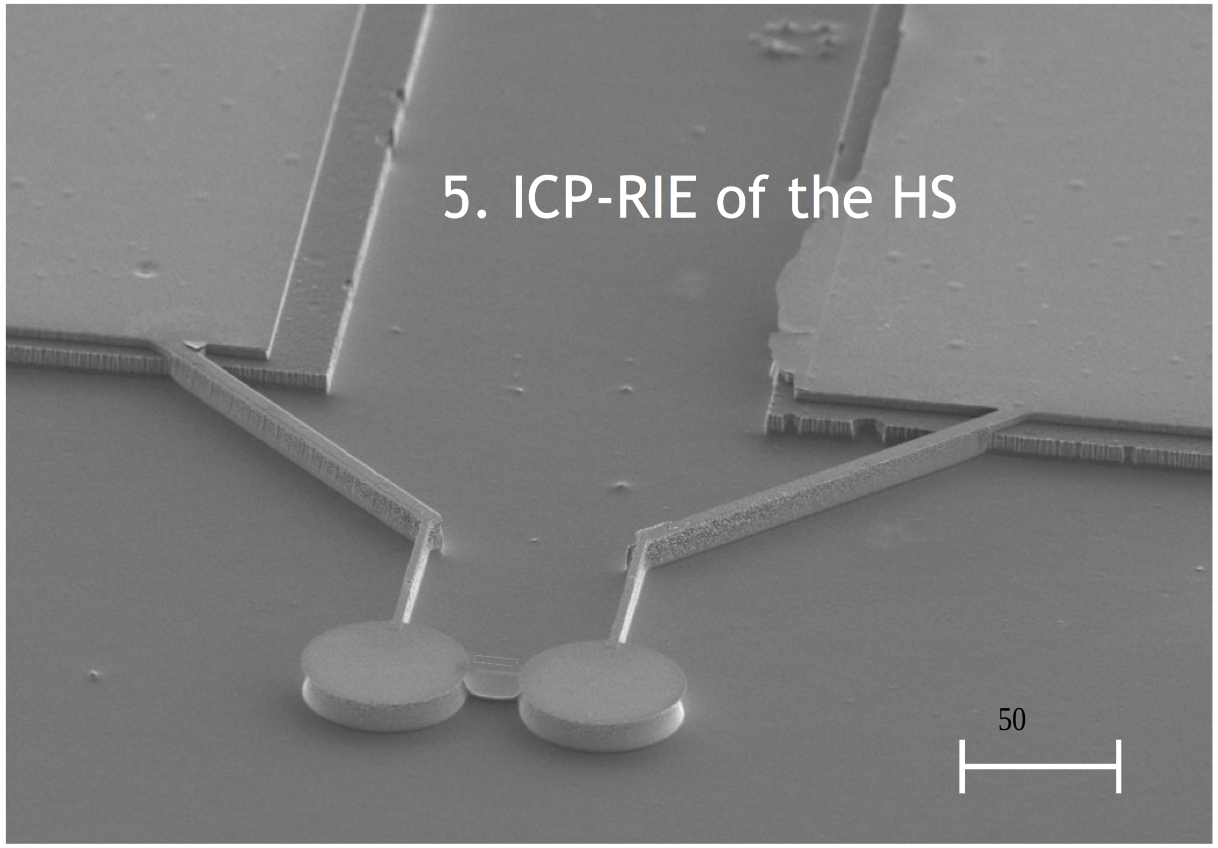
2. SiO_2 sputtering

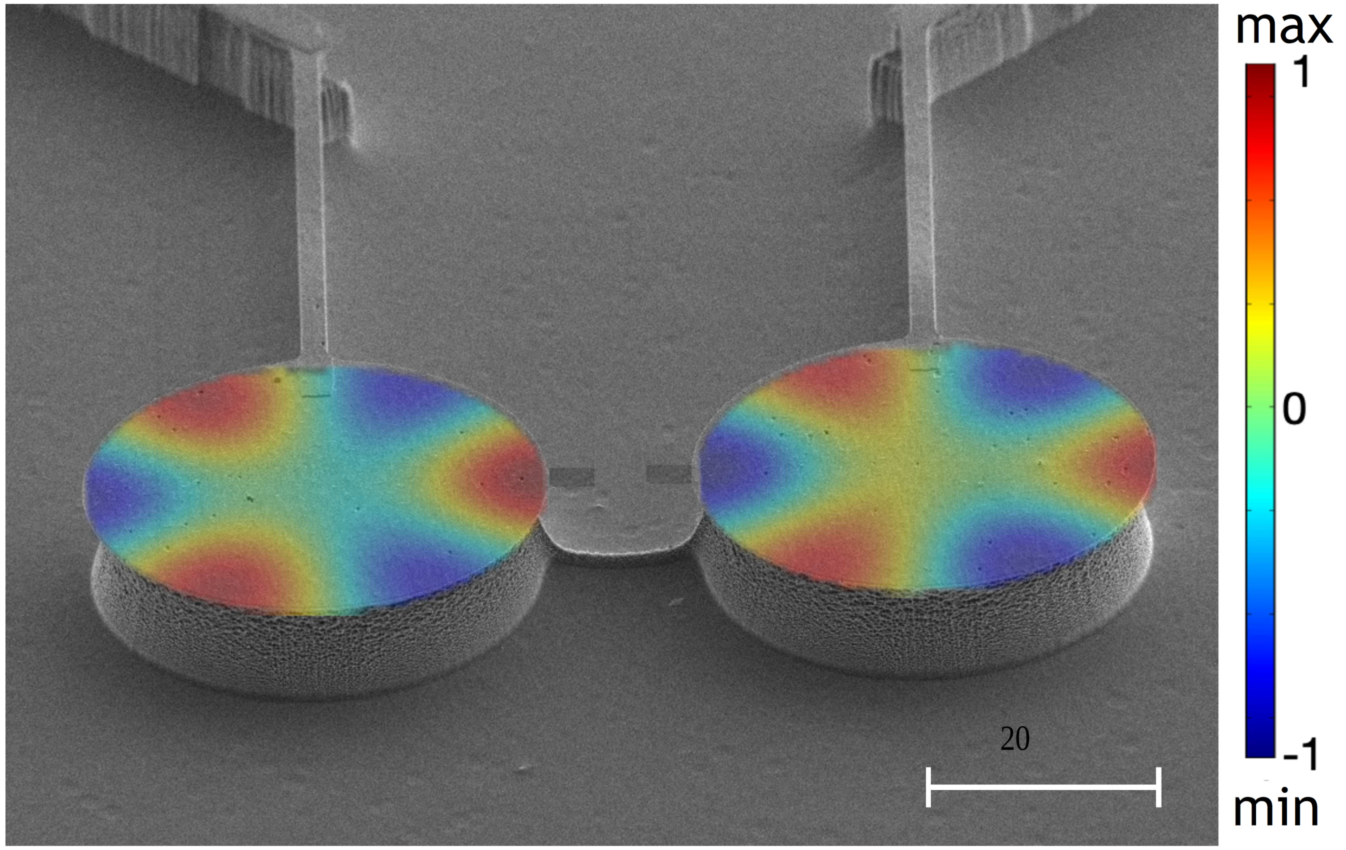
3. Aligned EBL + SiO_2 etching



4. Aligned EBL + metal evaporation

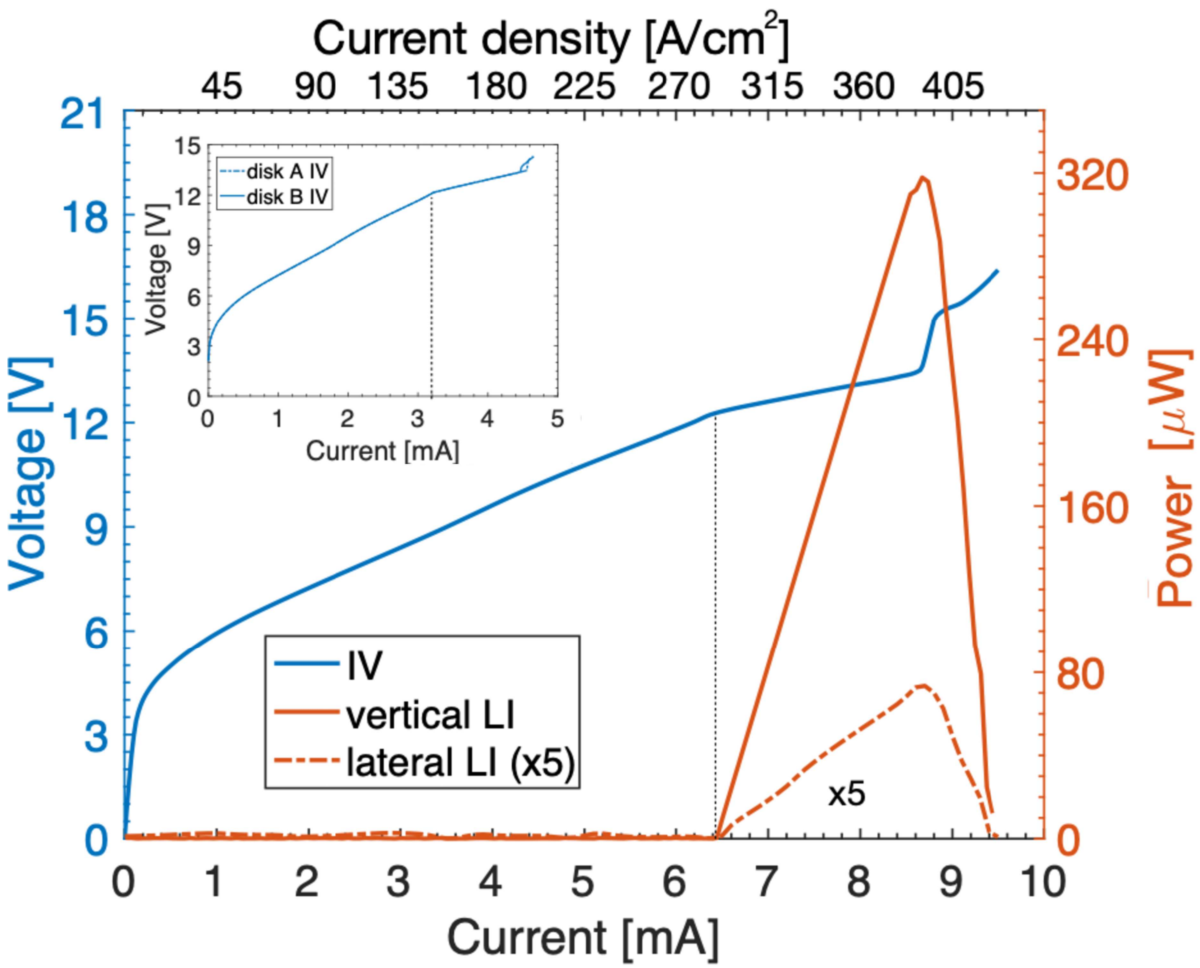


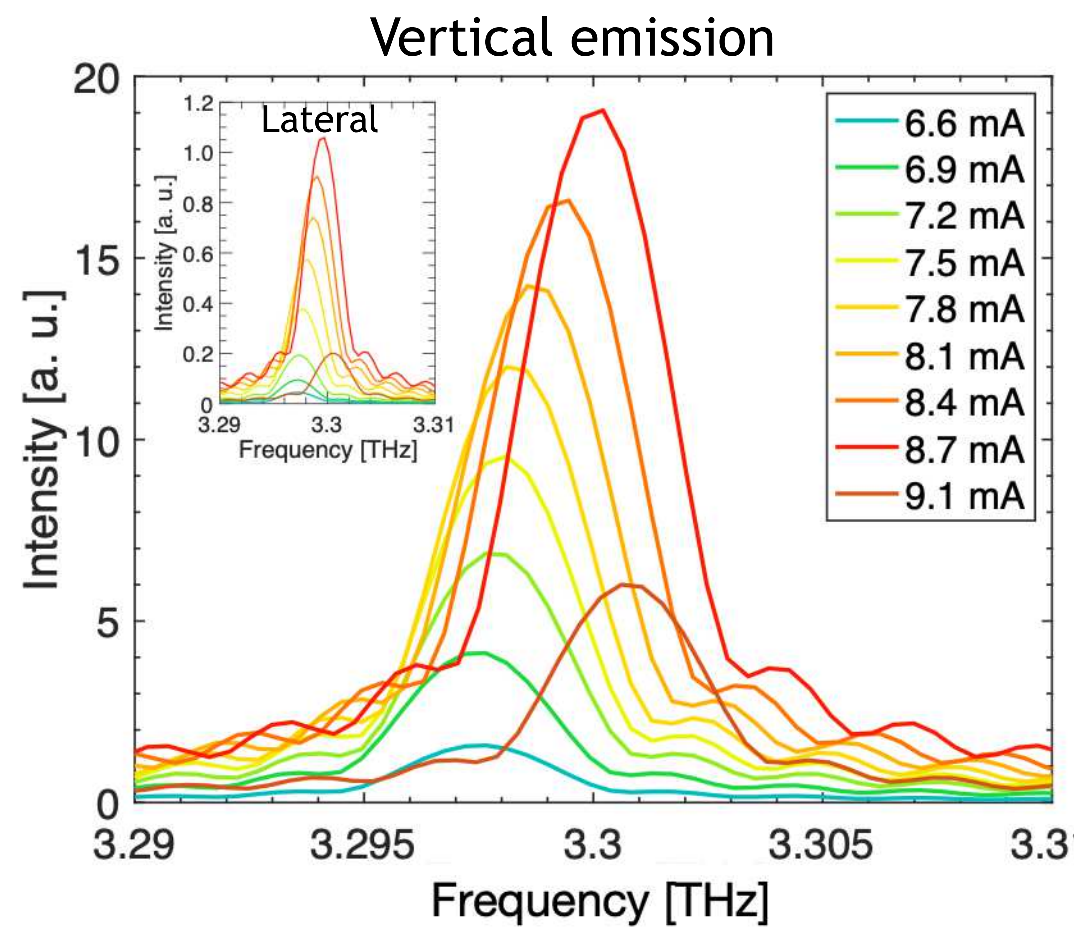




Laser operation

Simultaneously and equally pumping both microdisks at 10 K:





6.4 mA threshold current, 320 μW (max),140 mW/A power efficiency

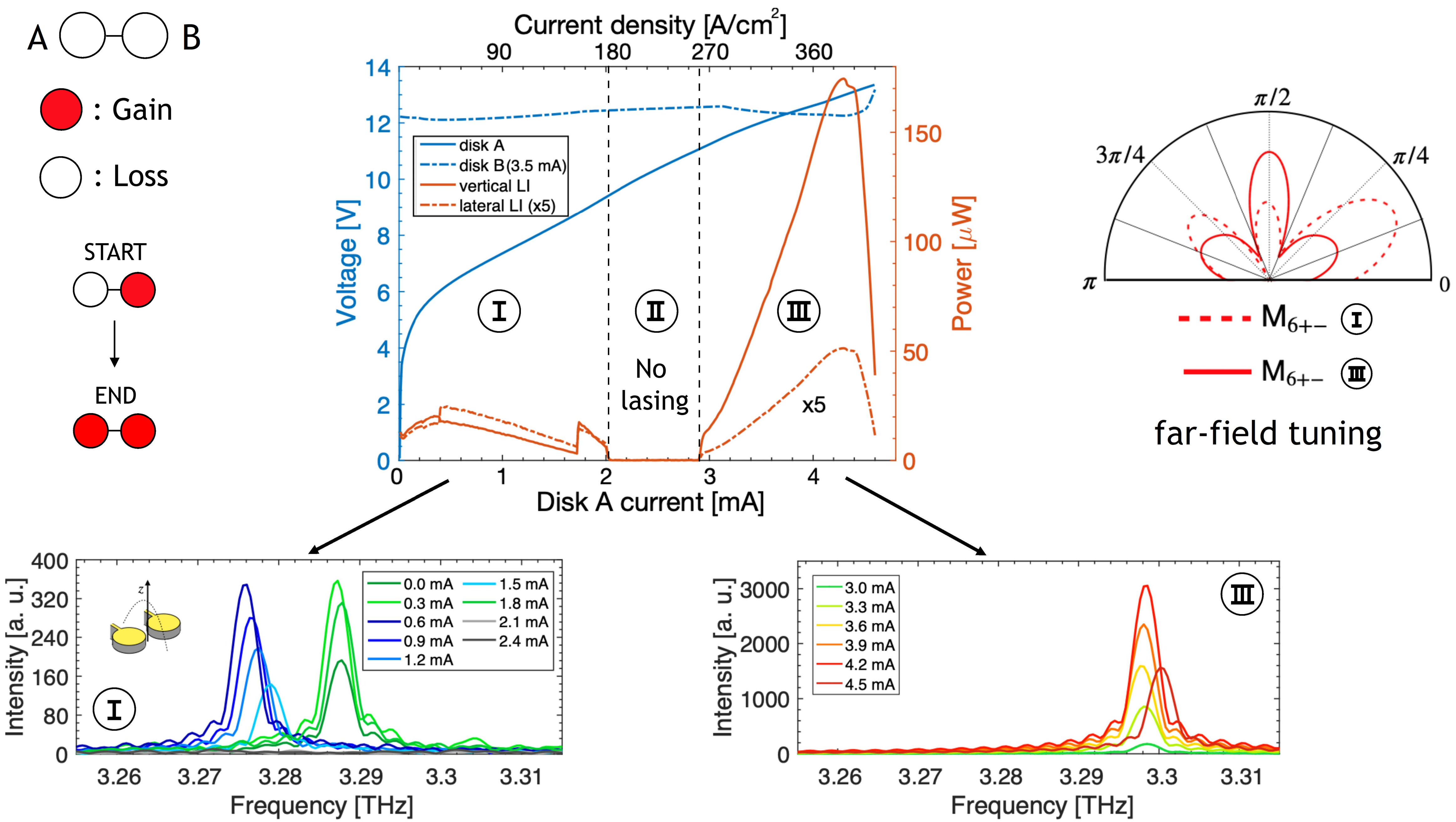
single mode CW vertical emission at 3.3 THz

(lateral to vertical emitted power ratio η~20)

A. Ottomaniello et al., *Optics Express*, 2021, https://doi.org/10.1364/OE.430742

Spatial control of injection

Varying the current in Disk A while keeping fixed at 3.4 mA that of Disk B:

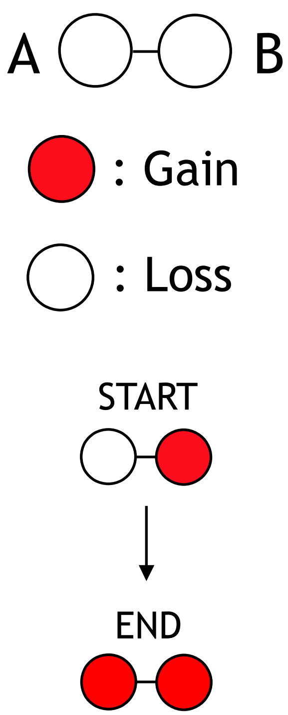


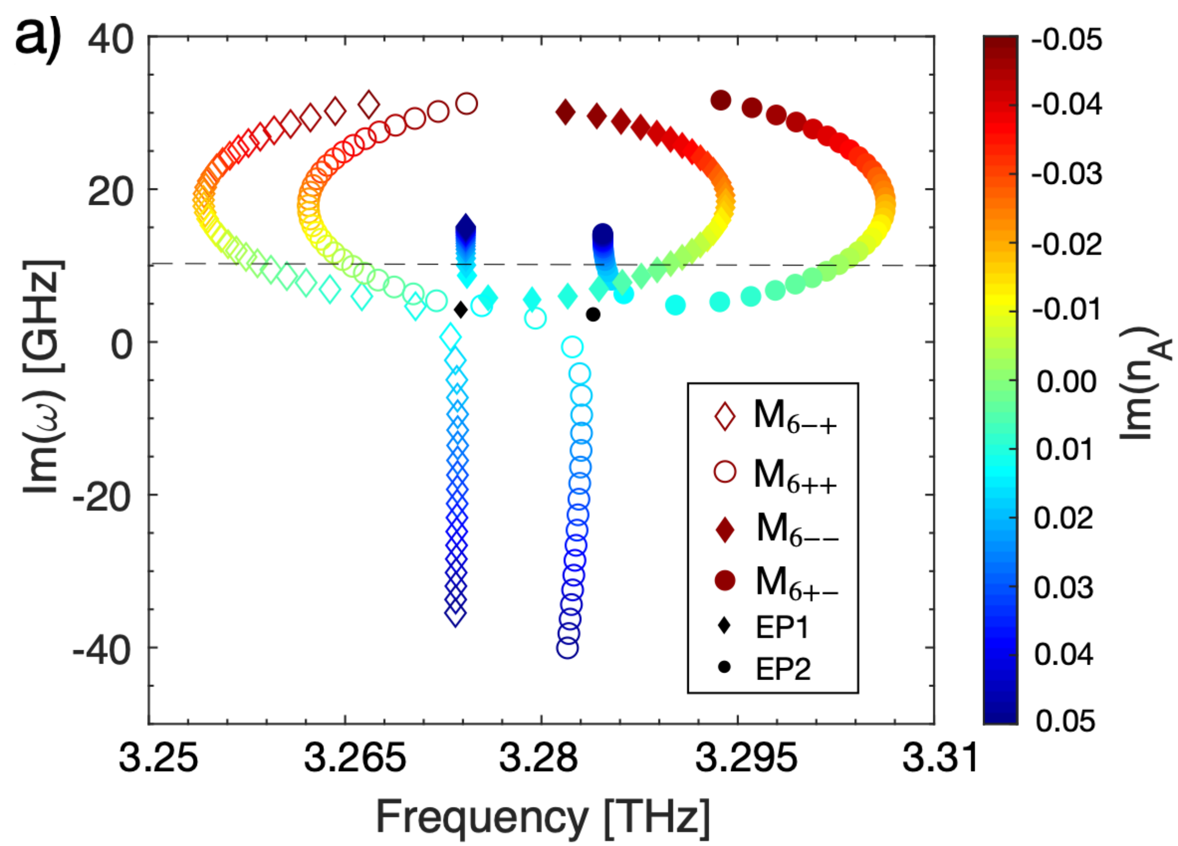
Laser operation control by spatially controlling gain and loss

A. Ottomaniello et al., *Optics Express*, 2021, https://doi.org/10.1364/OE.430742

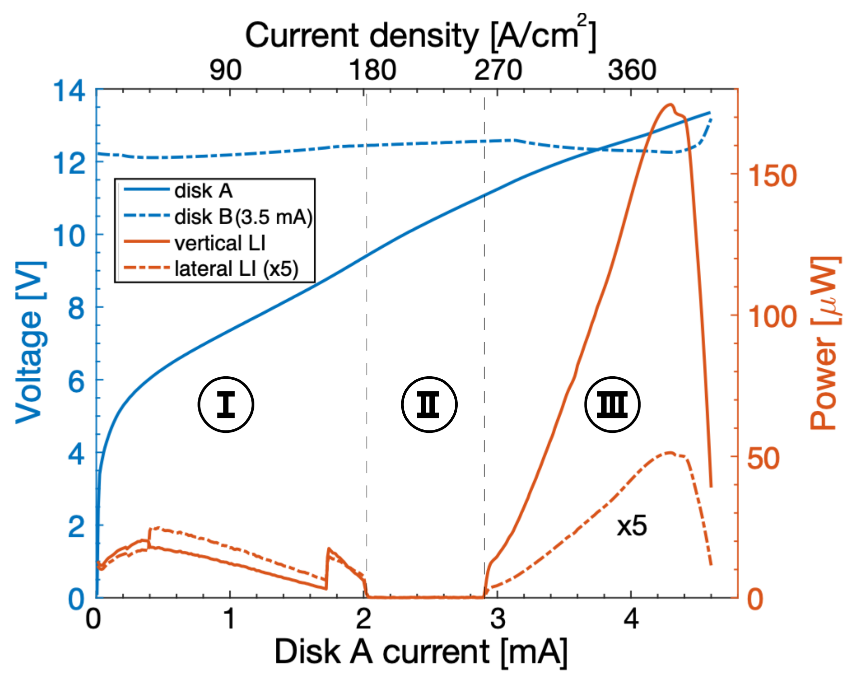
Spatial control of injection

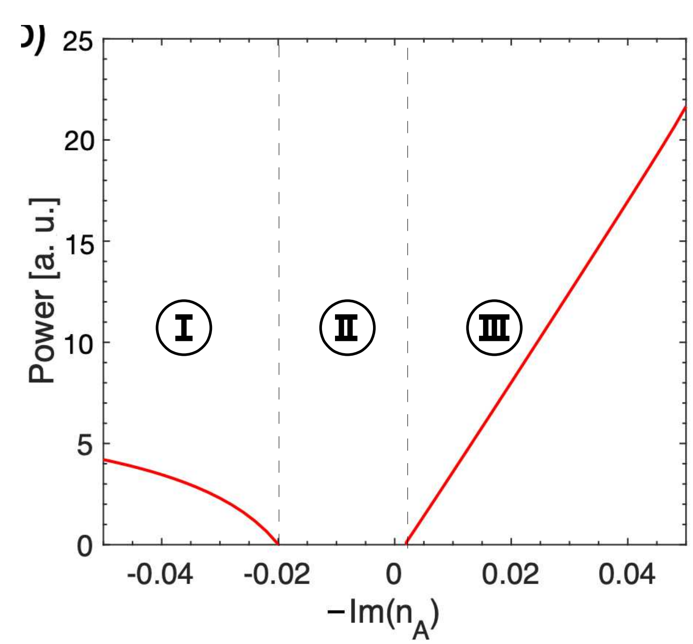
Varying the current in Disk A while keeping fixed at 3.4 mA that of Disk B:





Two non-Hermitian singularities: exceptional points (EPs)

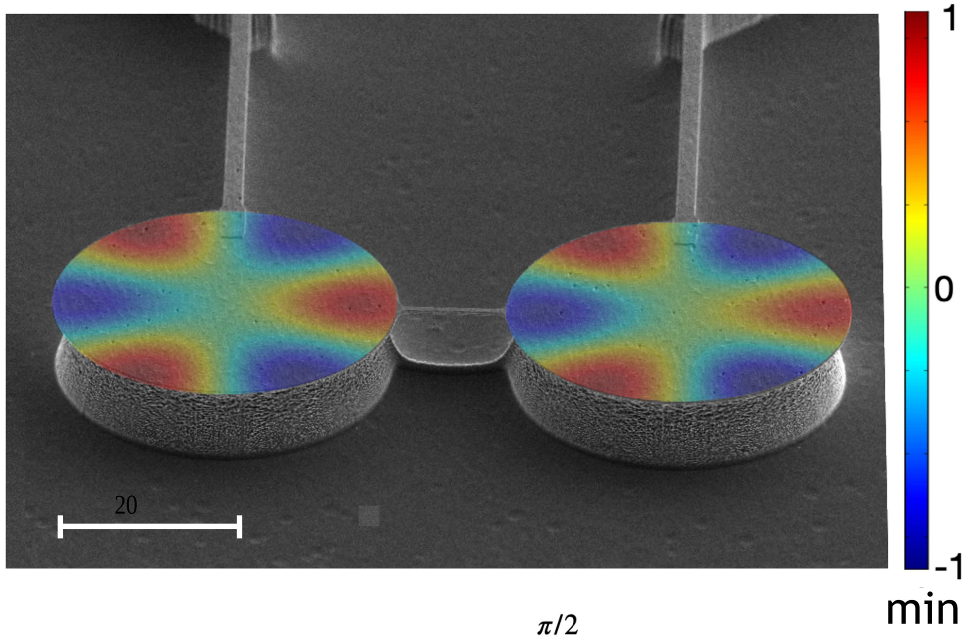


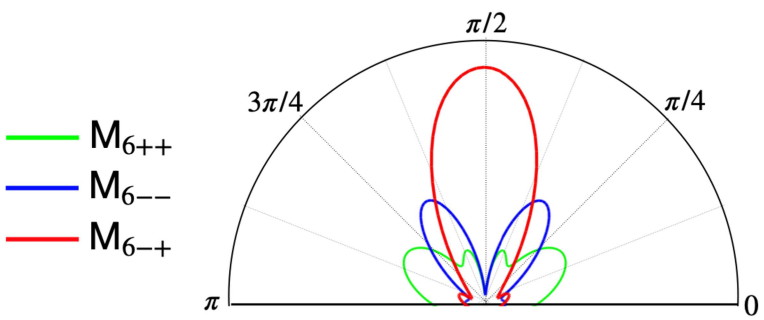


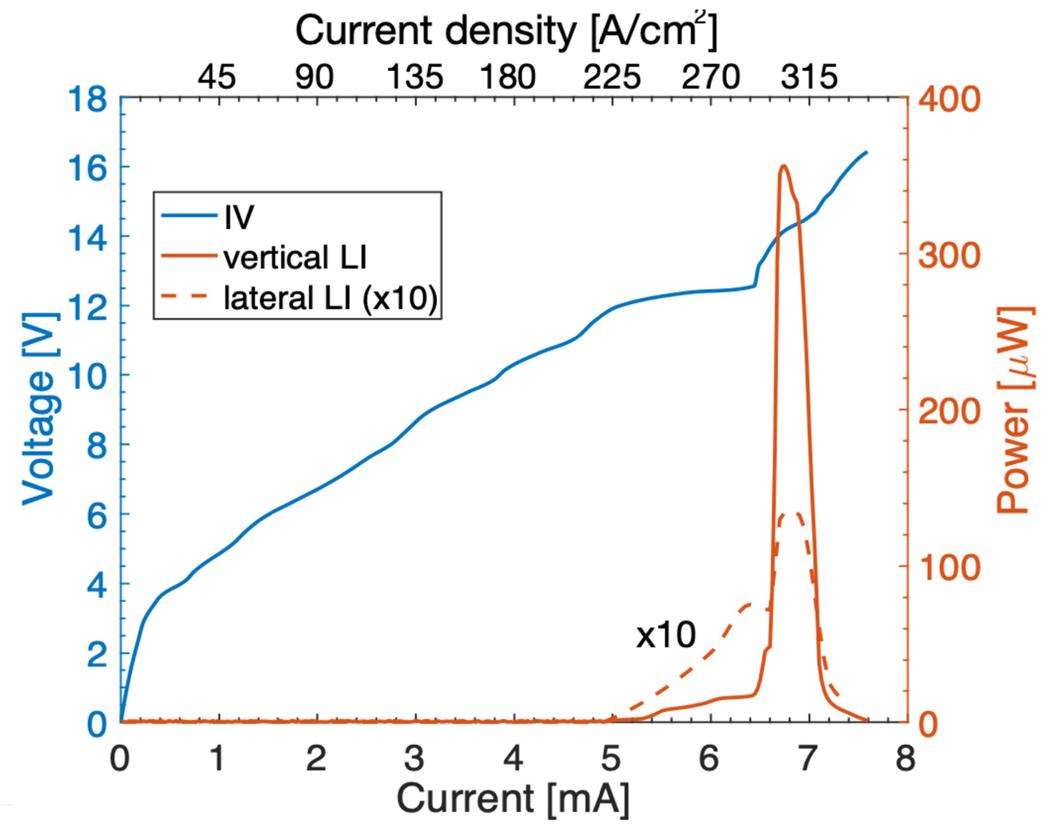
Reversal of the laser pumping dependence

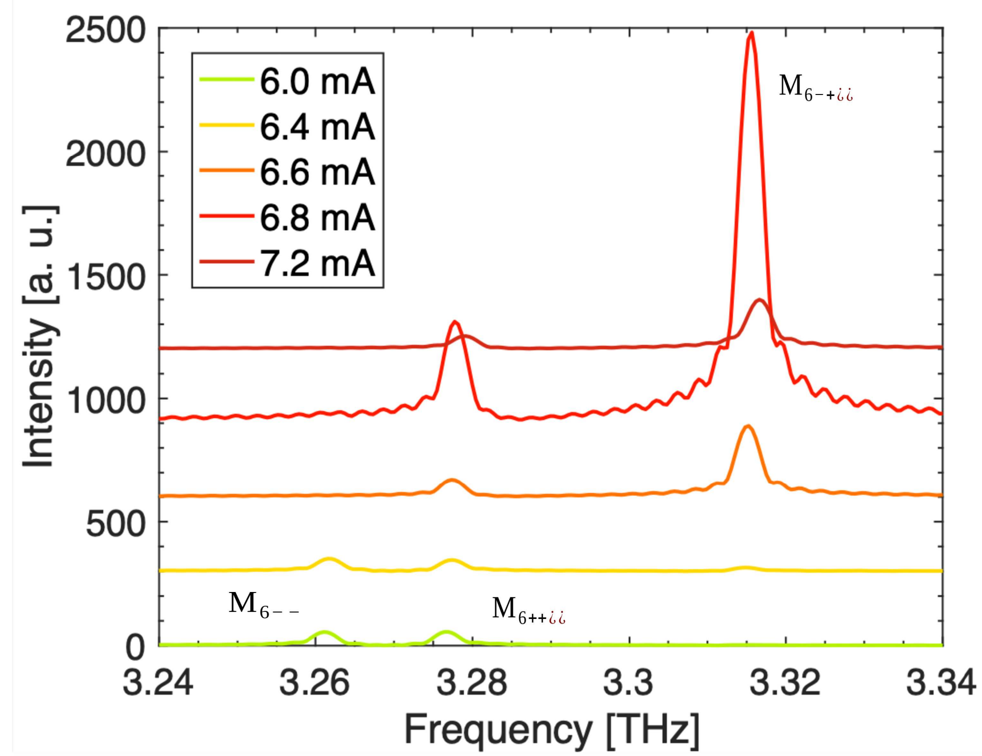
Laser operation: design 2.0

High enhancement of the out-coupling performance by adding the suspended bridge:









360 μW max emitted power in CW

record high slope efficiency of ~900 mW/A

strongly vertical collimated emission (η>160)

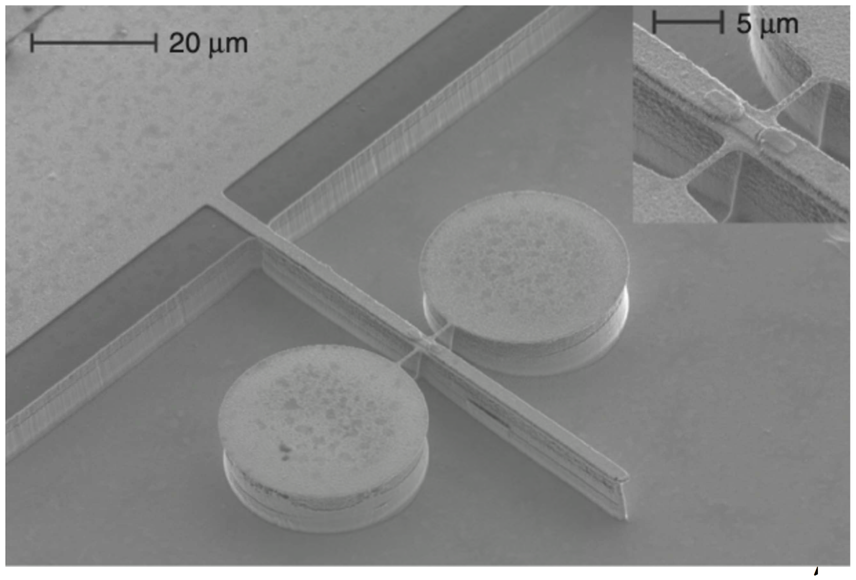
with <0.08 W of power consumption

A. Ottomaniello et al., *Optics Express*, 2021,
https://doi.org/10.1364/OE.430742

Perspectives

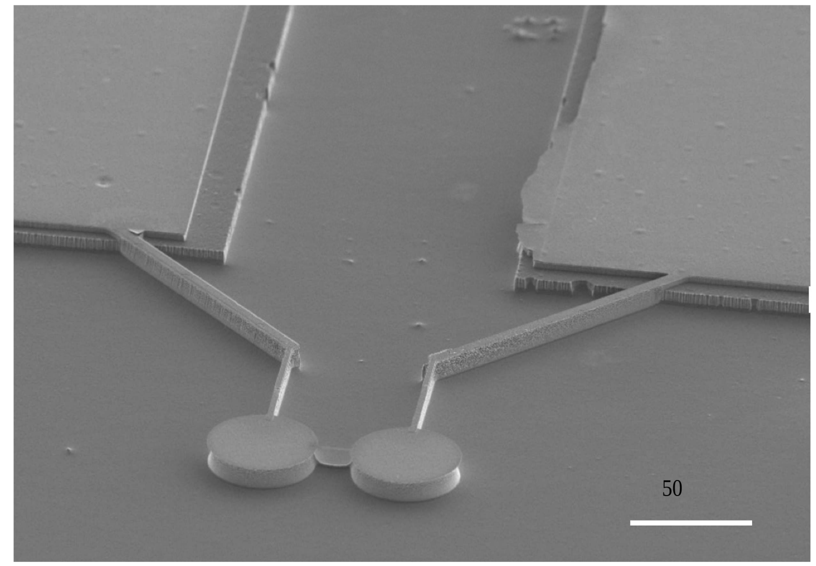
We developed different designs of microcavity lasers:

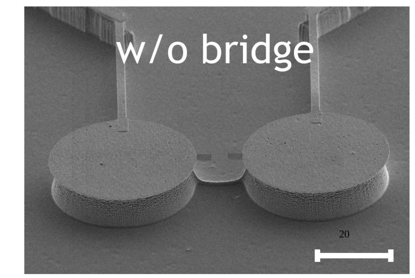
1)

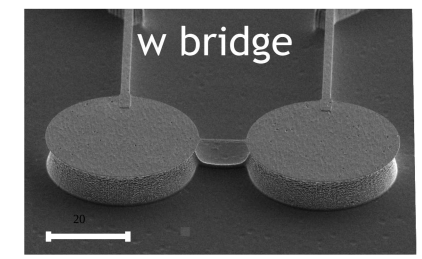


L. Masini et al., *Light: Science & Applications*, 6, e17054 (2017).

2)







Ottomaniello et al., *Optics Express, 2021* https://doi.org/10.1364/OE.430742 .

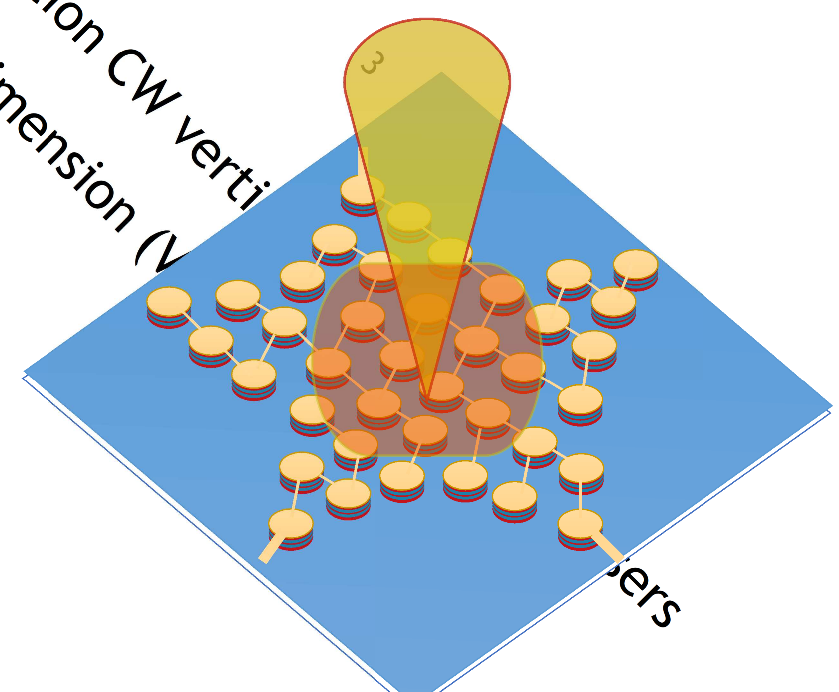
…ower consumption CW verti…

…n subwavelength dimension (V…

Arrays of massively integrated

and parallelized microcavity lasers

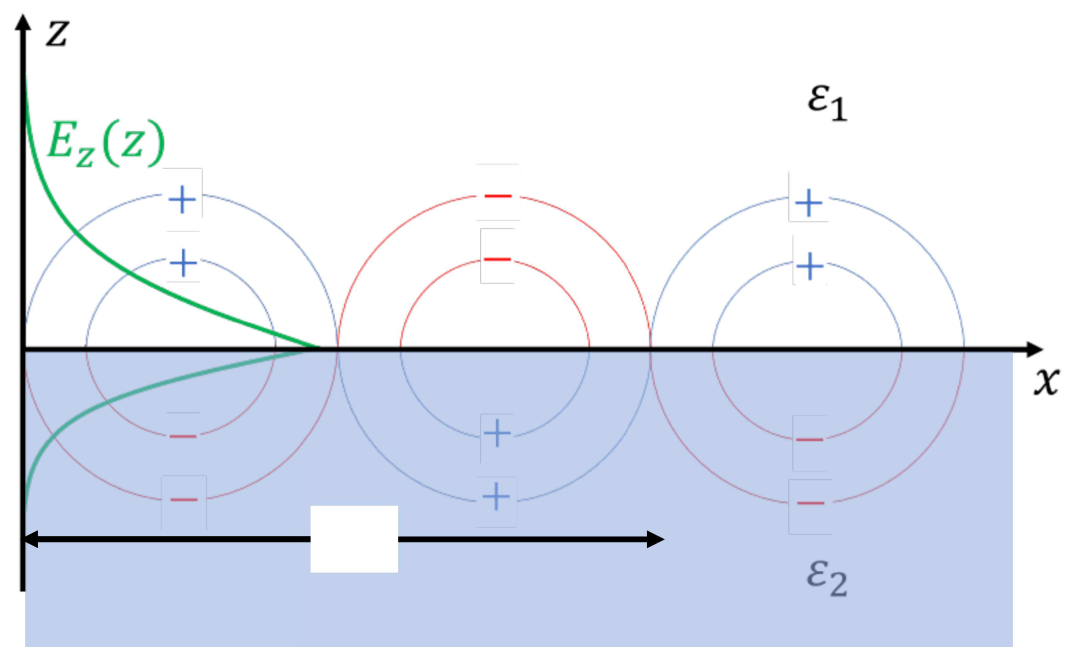
Multi-wavelength and with far-field tunability



…ers

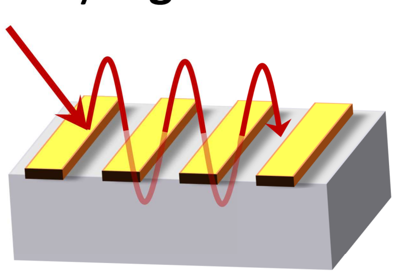
Graphene plasmons as cavity modes

Propagating EM waves coupled to electron oscillations inside a graphene sheet



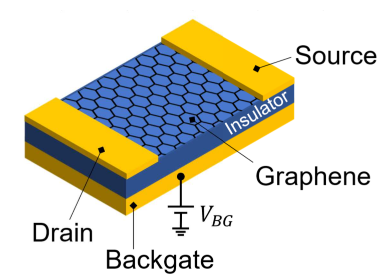
Plasmons confine light in **strongly subwavelength volumes:**

Very **high momentum mismatch**



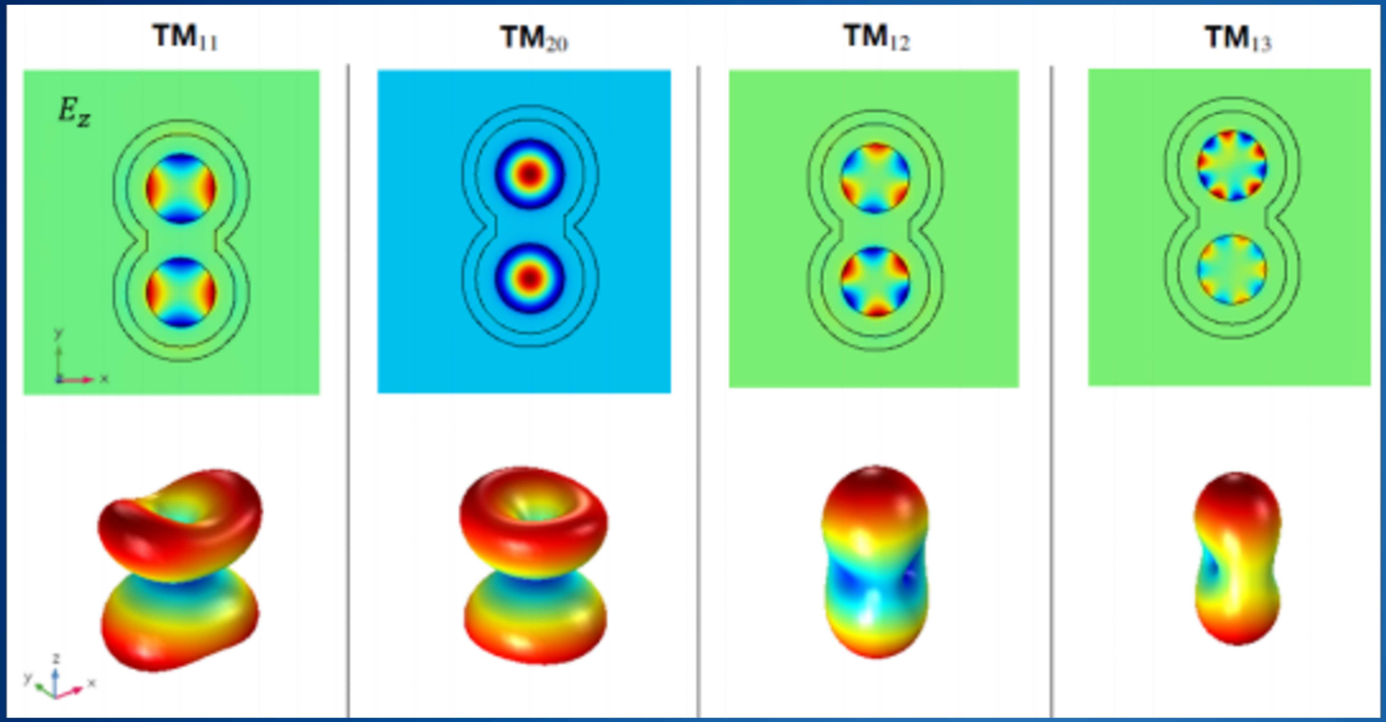
Metallic Arrays

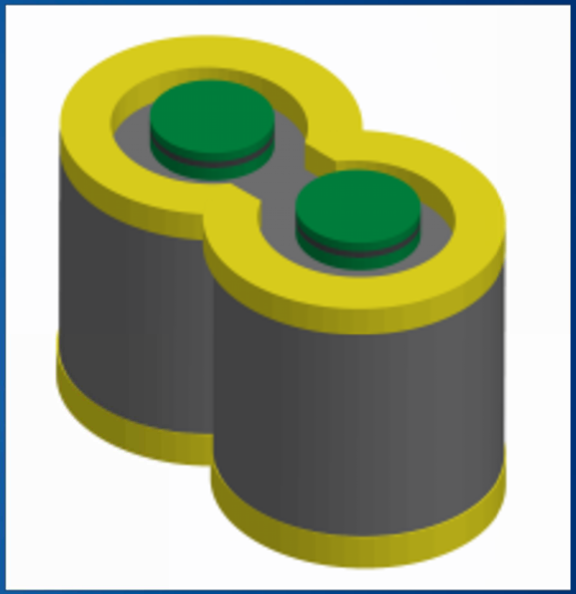
Electrically **tunable dispersion relation**



FET geometry

Vertical emission in graphene microdisk QCLs



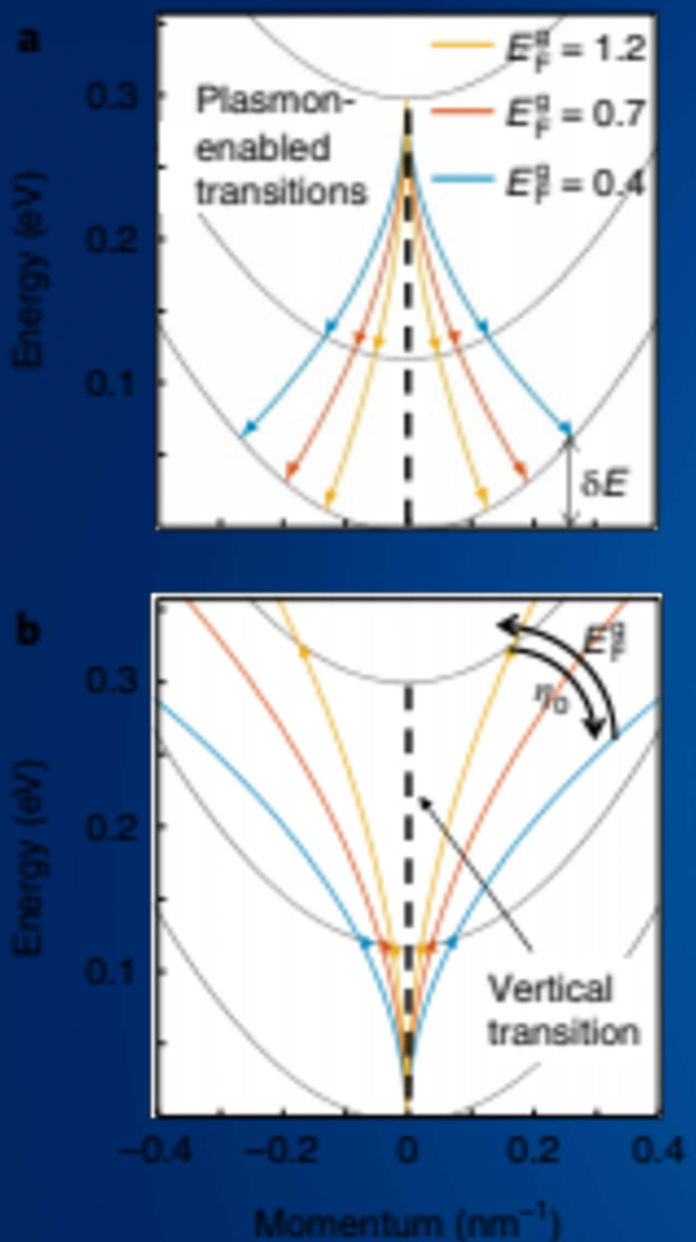


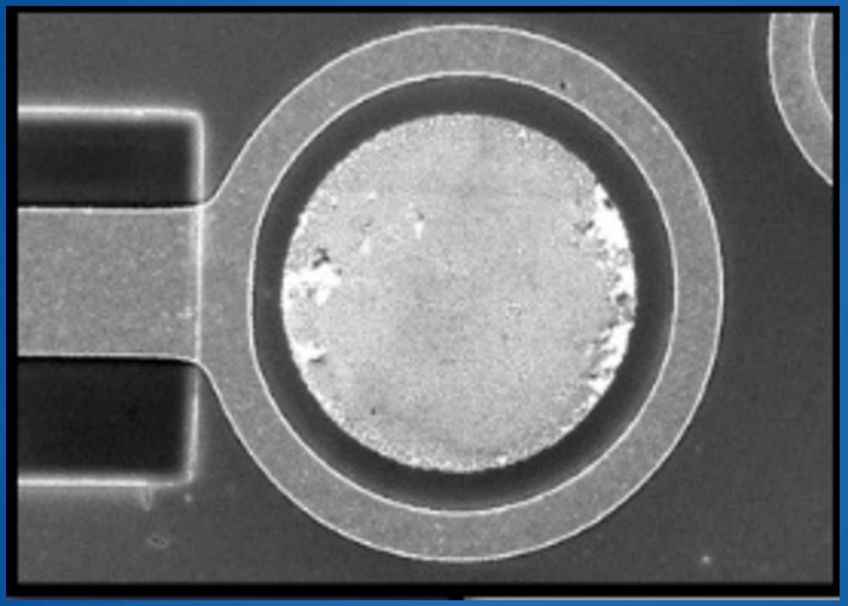
Coupled disk geometry with graphene waveguide

NATO OTAN

This project is supported by: The NATO **Science** for **Peace** and **Security** Programme

Ultra-small devices





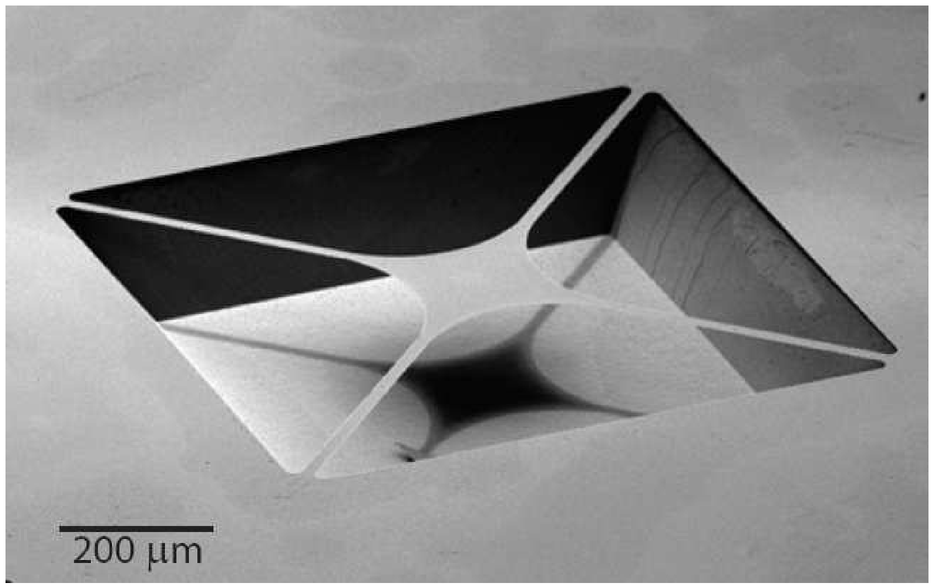
- High Purcell enhancement factors
- Low power consumption (Peltier)
- Large plasmon wavector could enhance gain
- Reduce cascade inhomogeneities

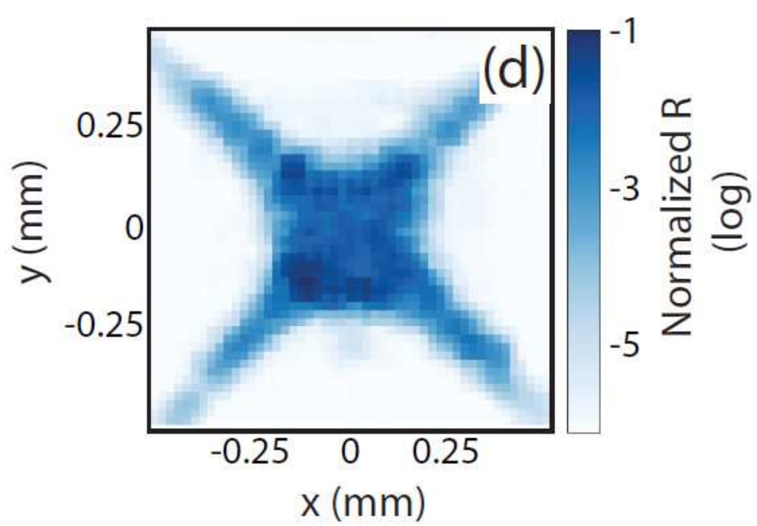
NATO OTAN

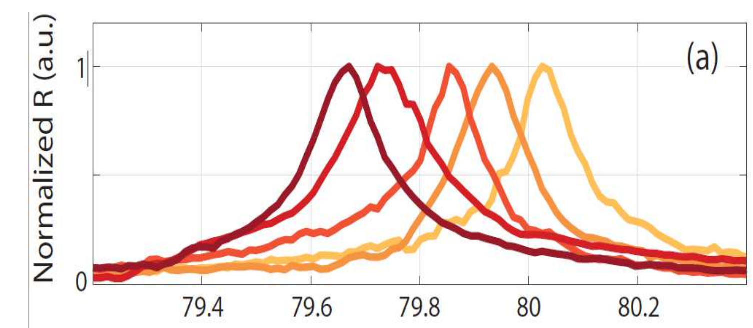
This project is supported by: The NATO Science for Peace and Security Programme

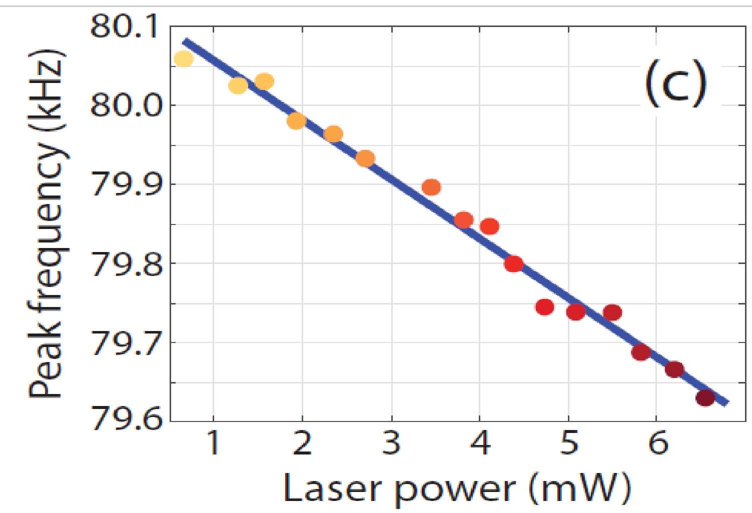
Opto-mechanical bolometric detection

An alternative approach:





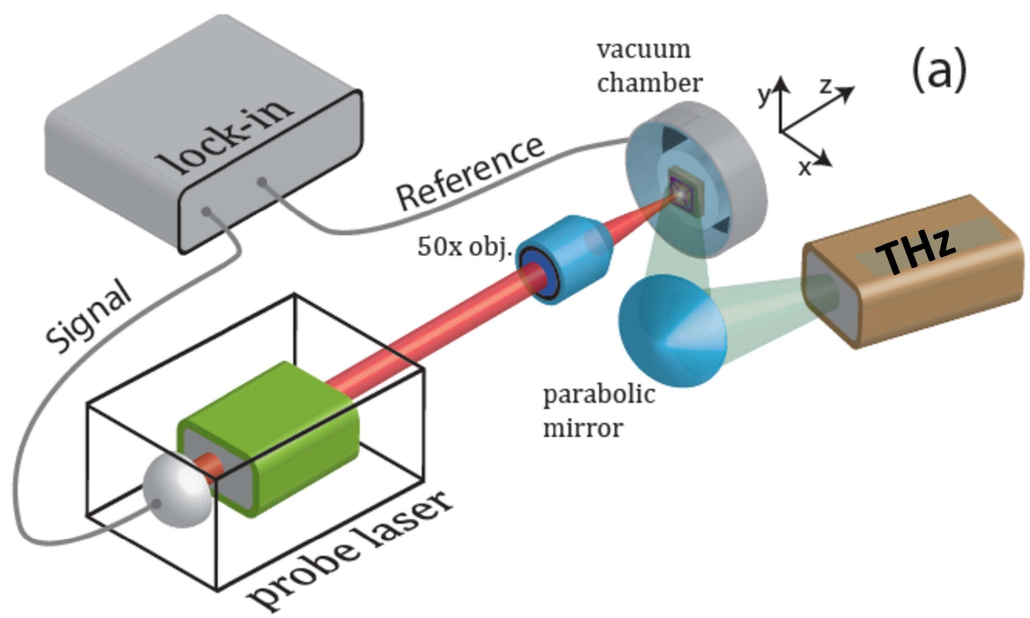


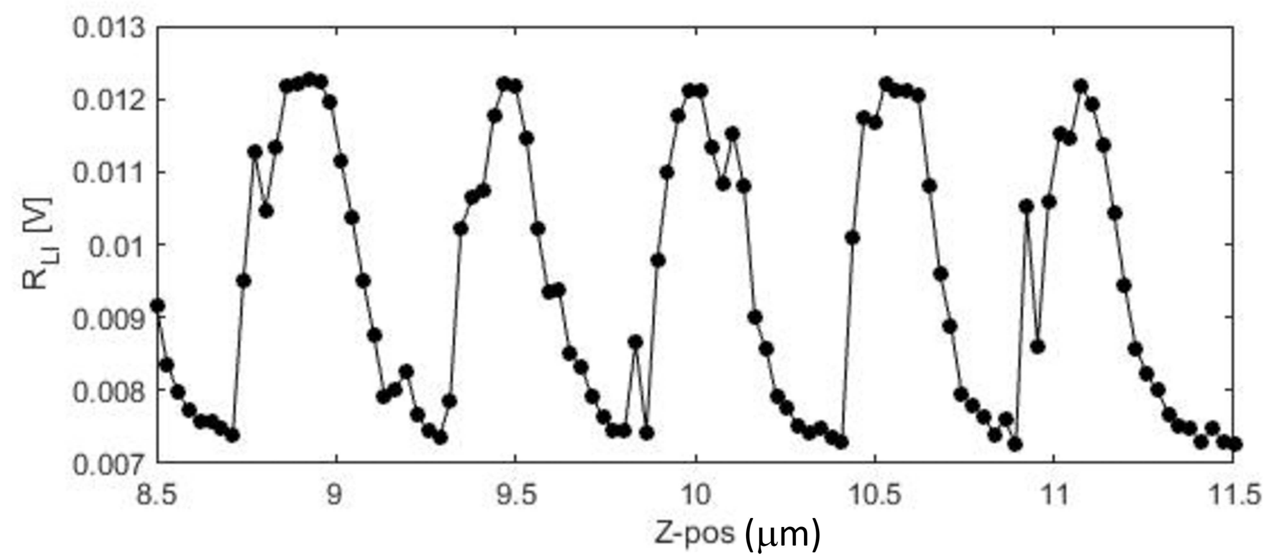


Suspended SiN membrane vibration is measured by self-mixing
The resonant frequency decreases with temperature
(thermal expansion relaxes tensile stress)
It can be applied to the detection of any radiation that release energy – THz as well!

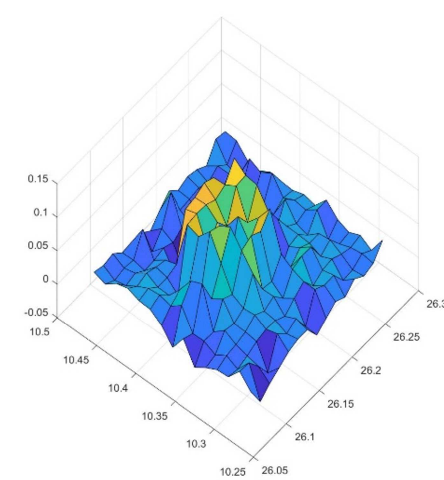
L. Vicarelli, et al., arXiv:2107.121270

THz Detection:

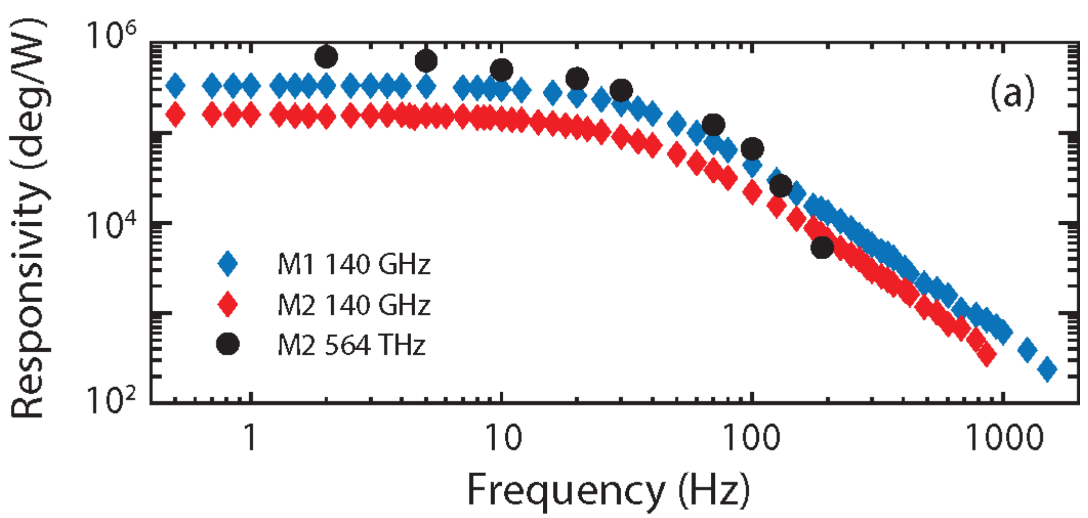


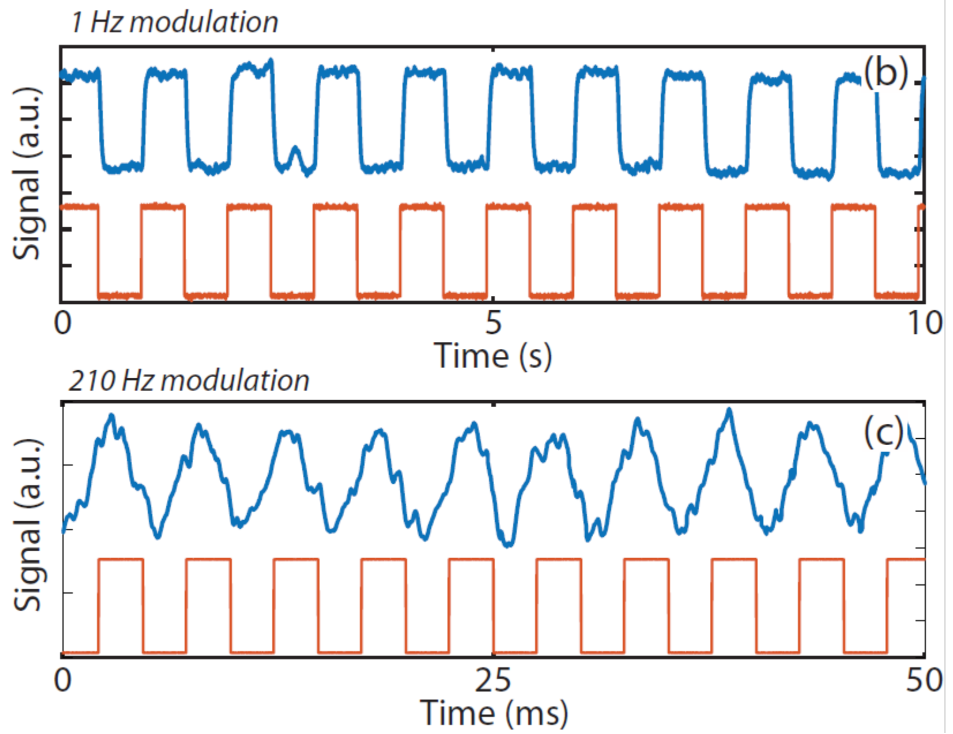


For a faster and better resolved graphene membrane detection we implemented a self-mixing scheme.
Sensitivity below to 1 nm resolution



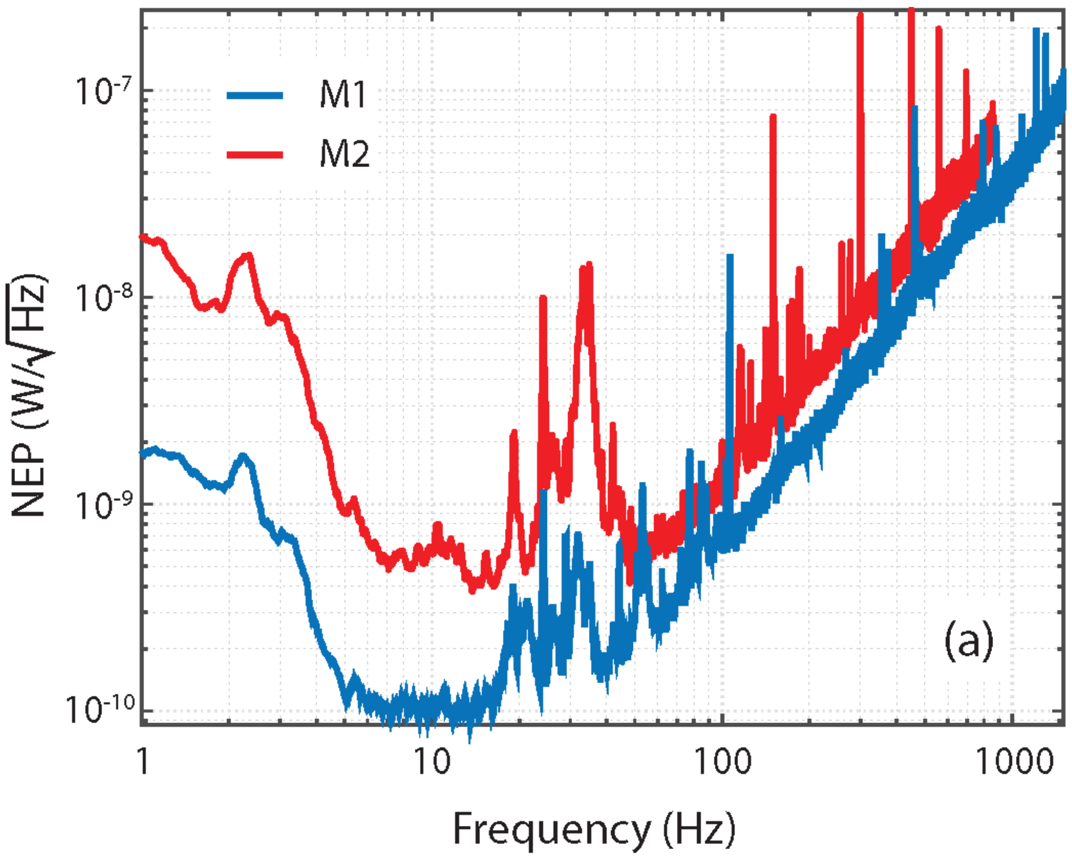
0.15THz detected!



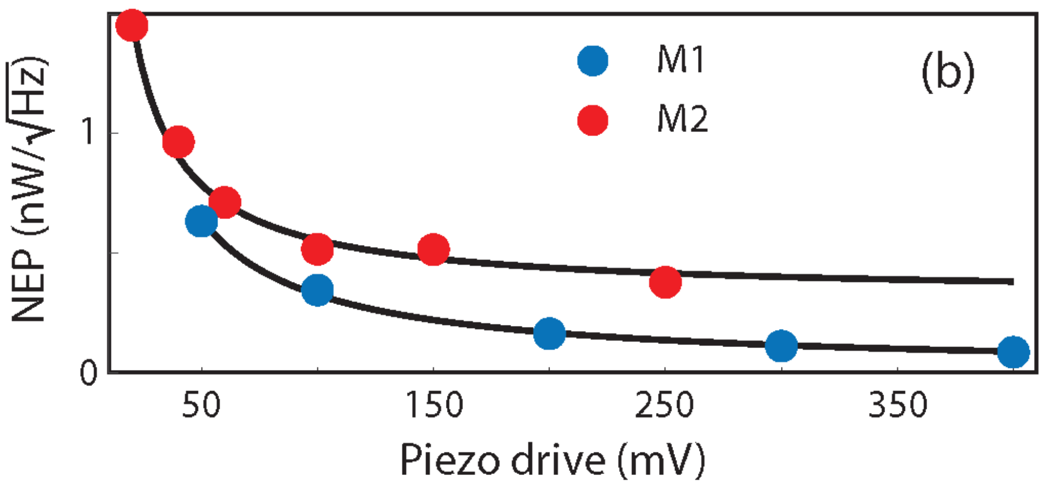


The response depends on the cooling and heating dynamics of the membrane
and on the quality factor of the membrane (the lower, the better!)
But still requires vacuum for operation

NEP 100 pW $Hz^{-1/2}$

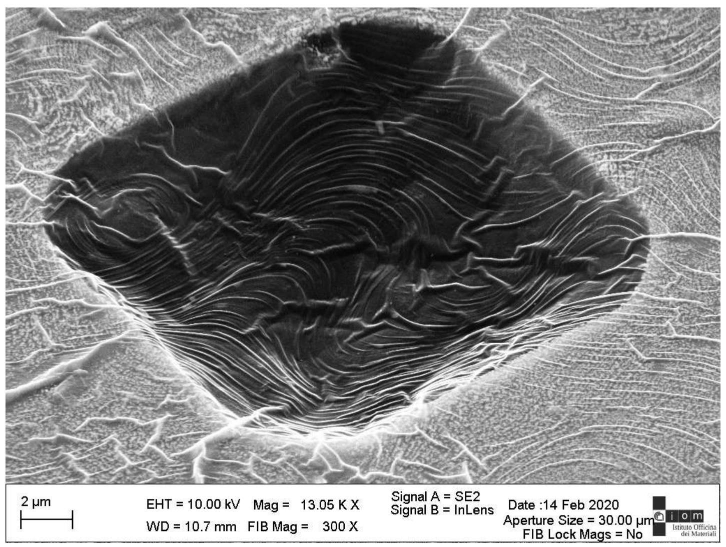


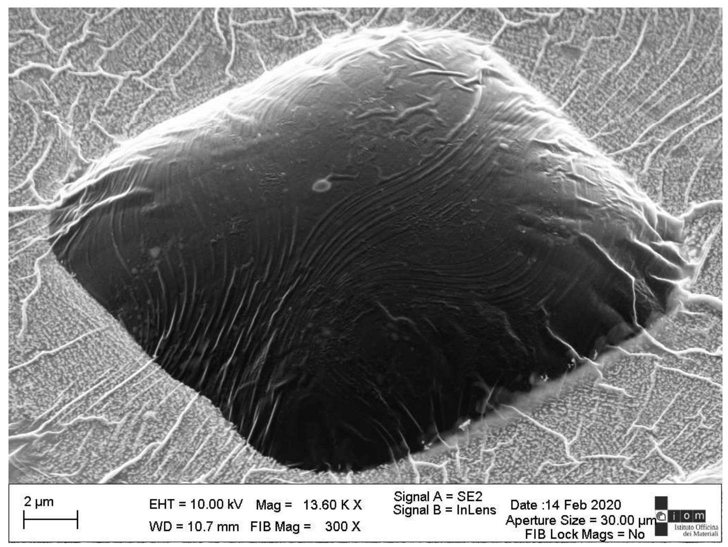
Lowest NEP ***100 pW $Hz^{-1/2}$***

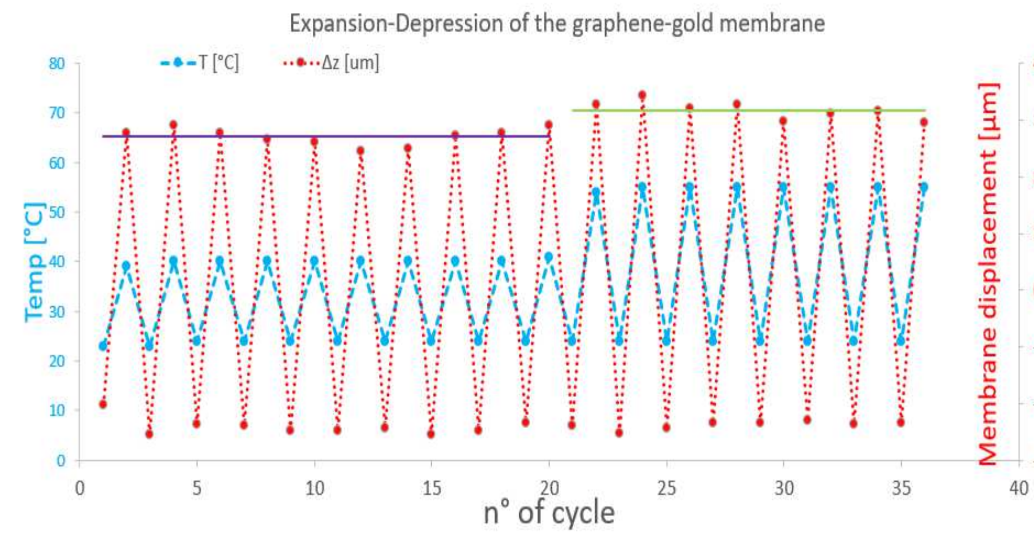


Increasing piezo driving voltage will decrease the NEP

Adhesion: solved!
Leakage solved!





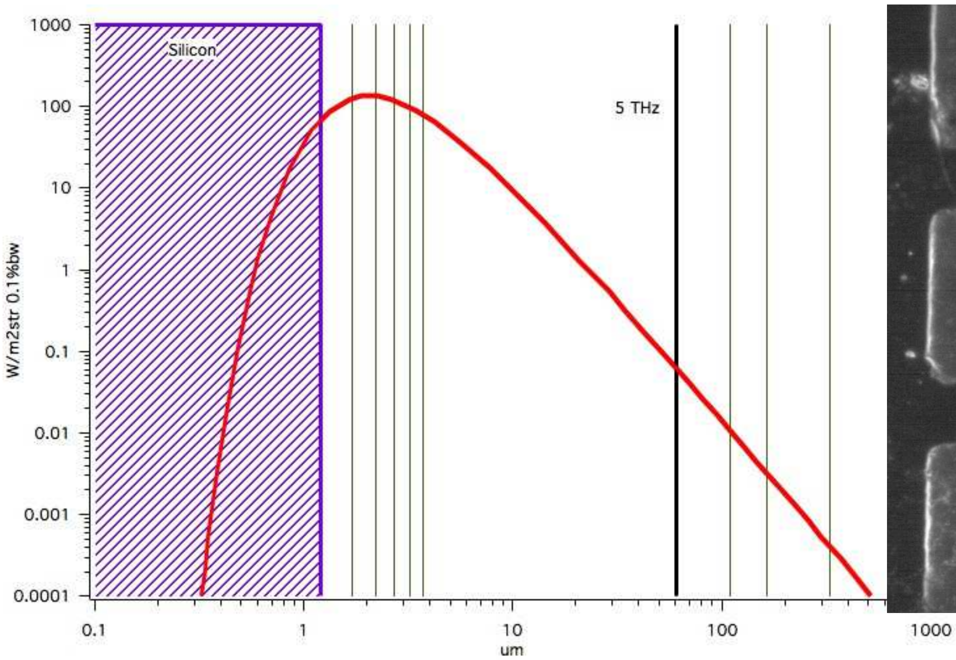


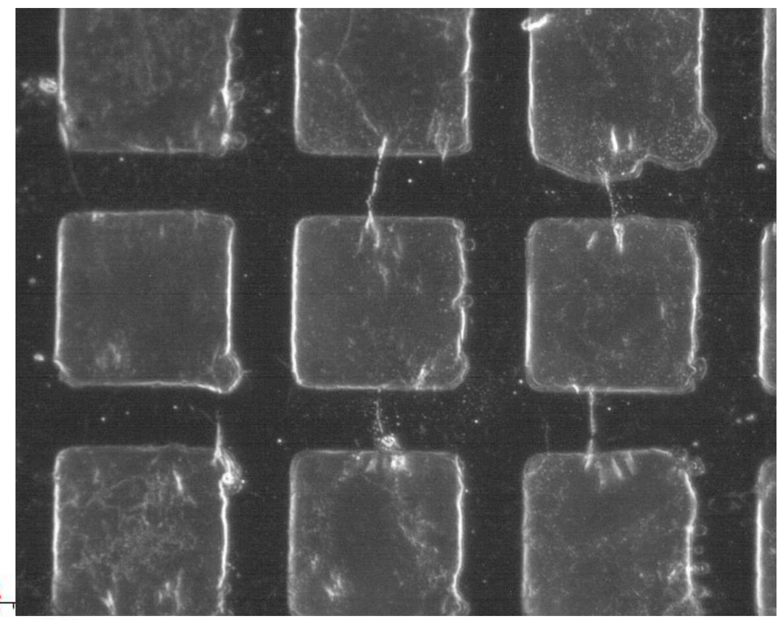
Graphene transfer protocol allows the fabrication of membrane able to withstand 10^5 Pa of pressure difference
Graphene cells under show reproducible deformation when exposed to thermal expansion cycles

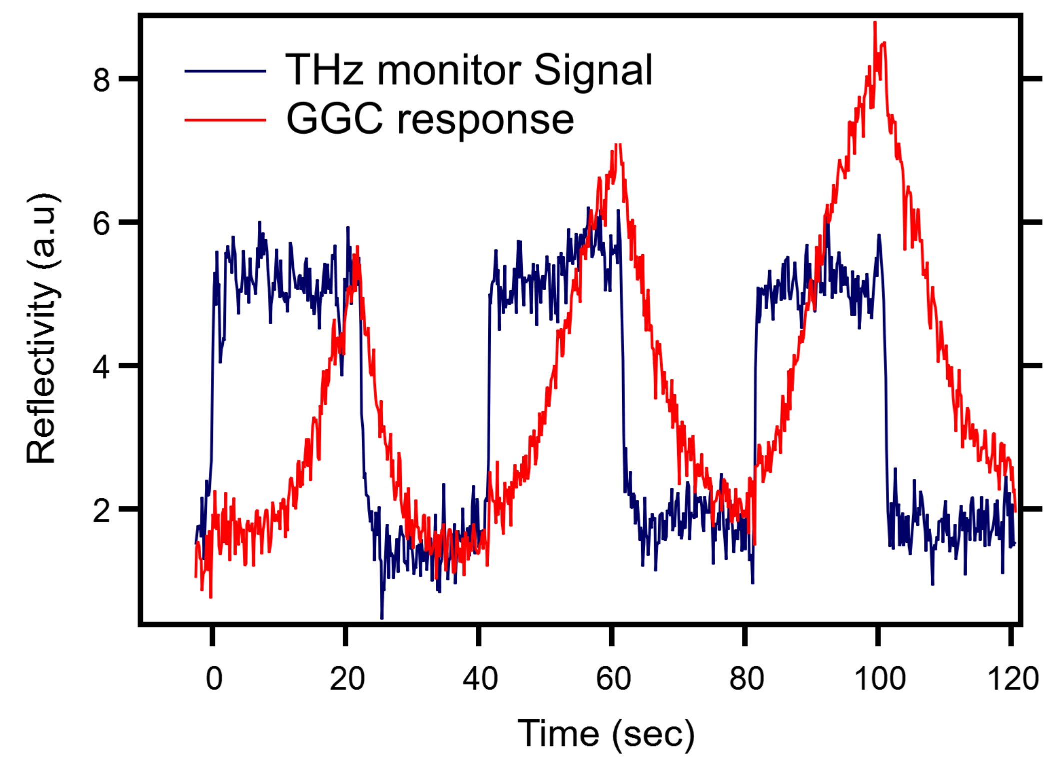
Courtesy of M. Lazzarino, CNR-IOM

ATTRACT

THz detection 1







GGC cells are illuminated from a globar source through a 5THz band pass filter,
The membrane deflection is monitored with a dark field optical microscopy
The response time is of the order of a second.

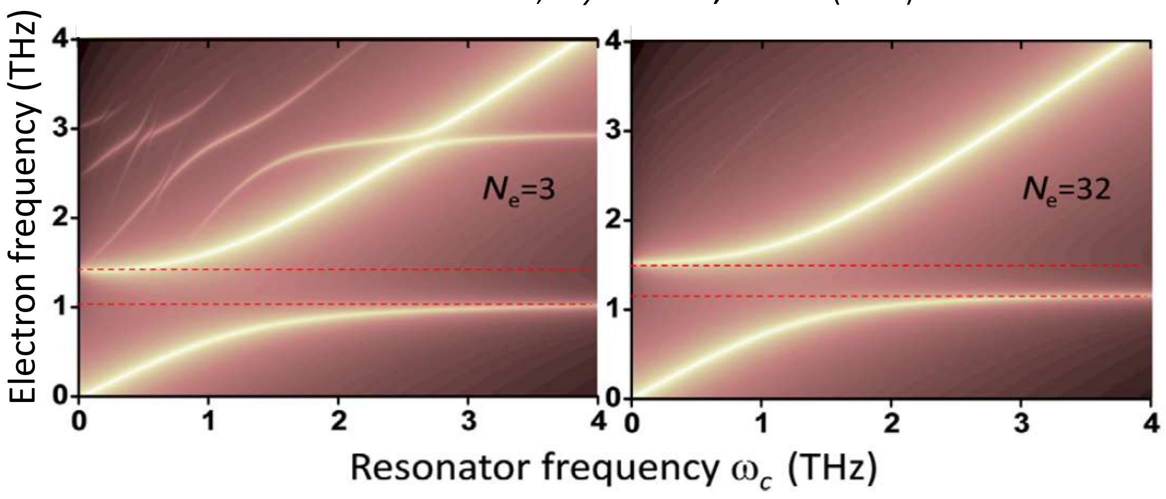
Courtesy of M. Lazzarino, CNR-IOM

Strong coupling in the few-electron regime

Quantum light sources

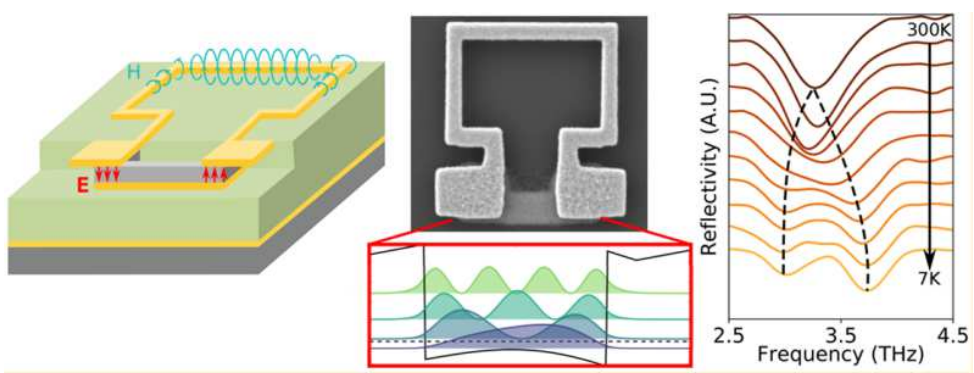
Few-electrons systems are interesting because of the strong quantum nonlinear effects

Y. Todorov *et al*, *Phys Rev. X* **4,** 041031 (2014)

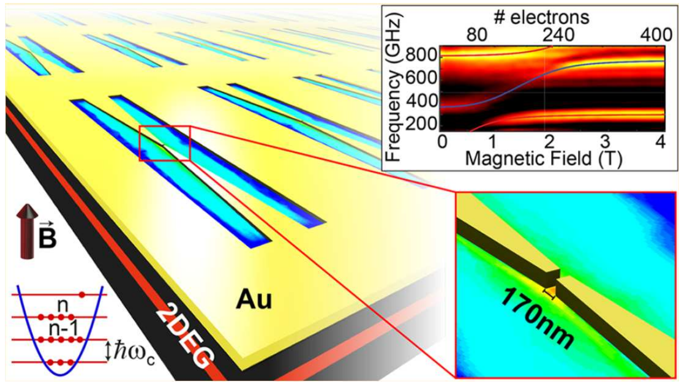


Challenging results have been achieved in systems with cumbersome fabrication or complex experiments

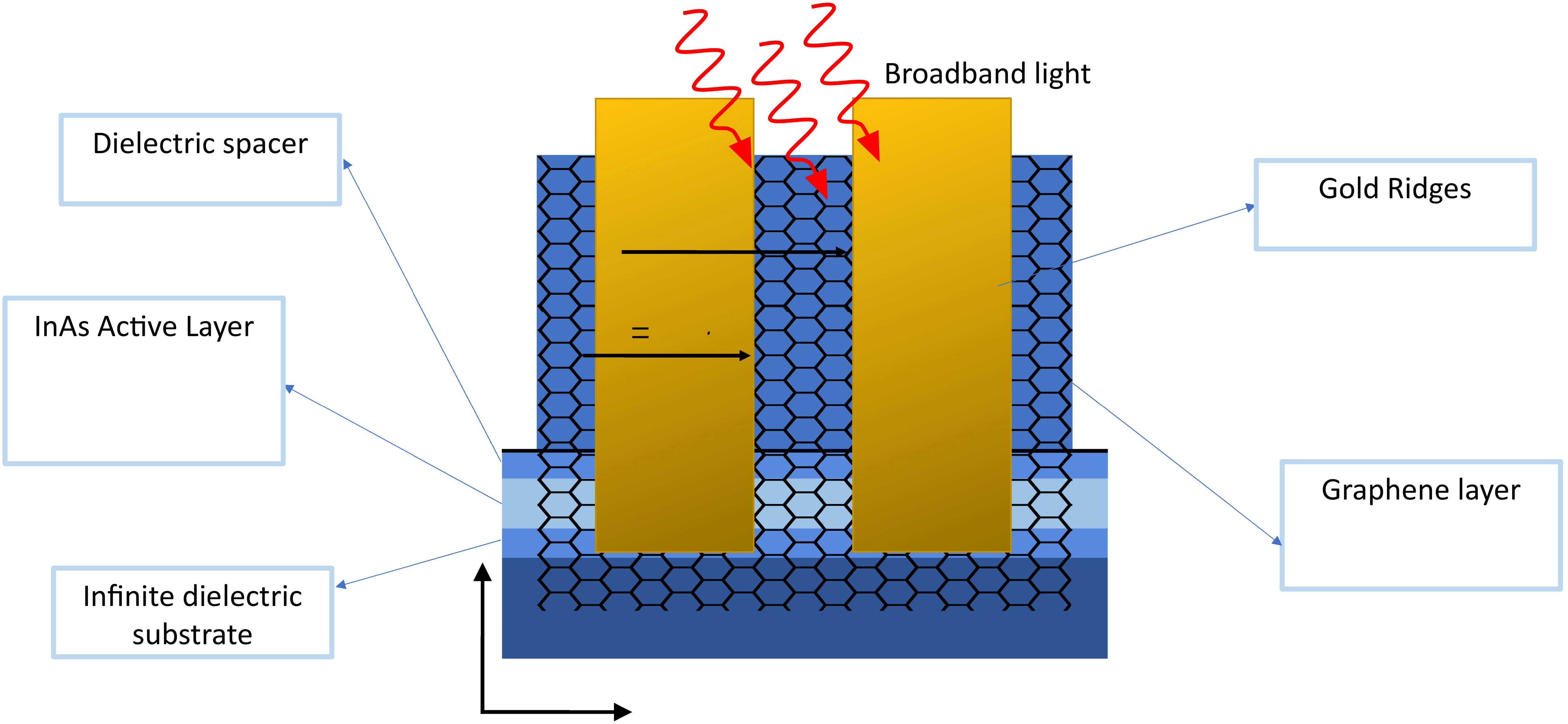
M. Jeannin *et al*, *ACS Photonics* **6,** 1207-1215 (2019)



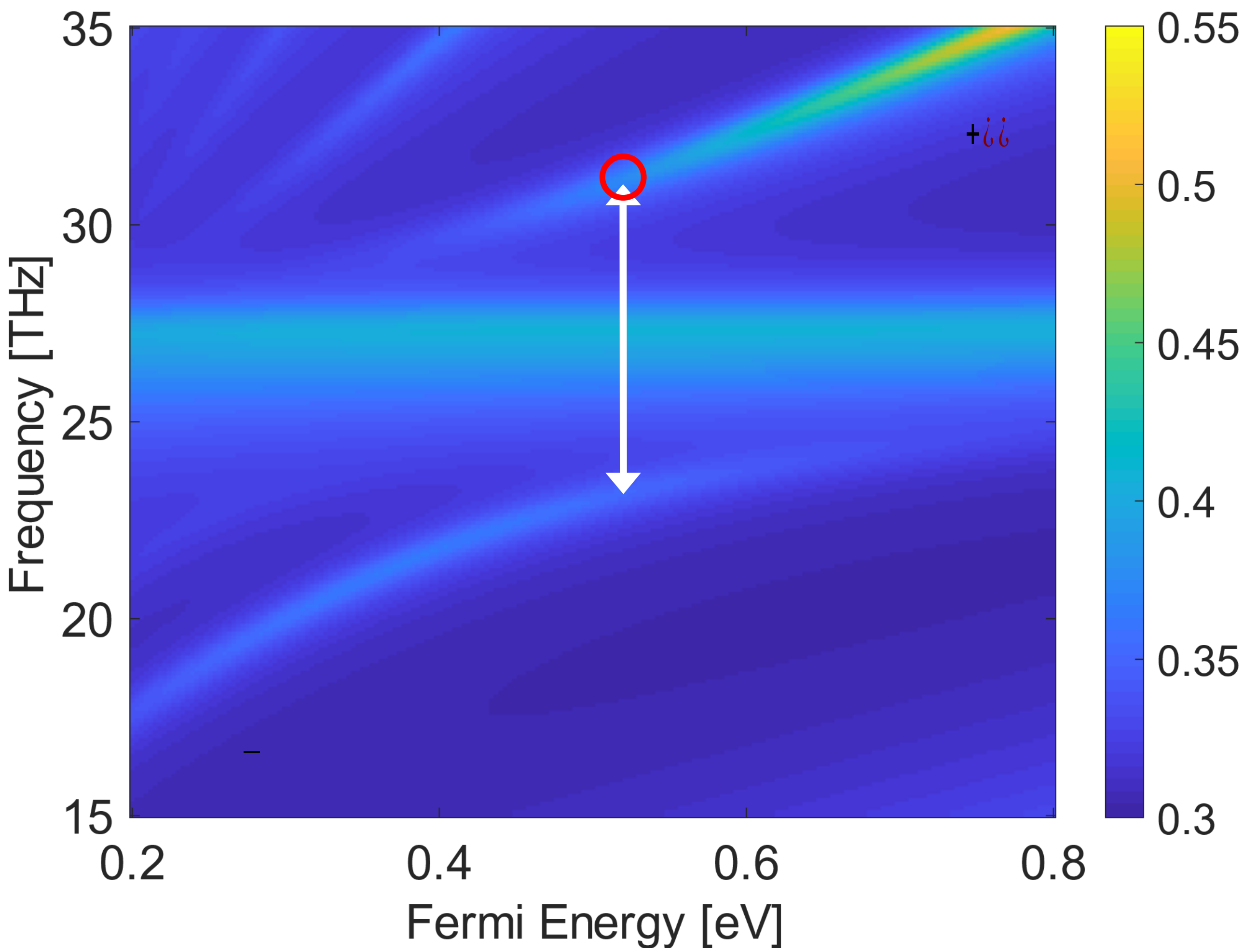
J. Keller *et al*, *Nano Lett* **17,** 7410-7415 (2017)



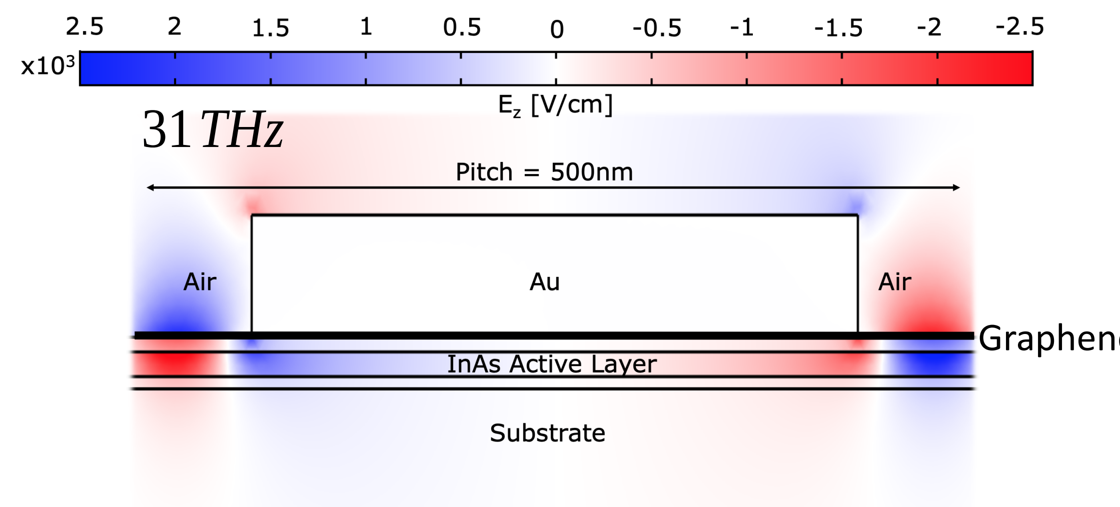
Graphene Plasmon launched by ridges



Resonant QW and GPs: dependence on



$\Omega \quad \sim 5\,THz$ → ~ 0.17

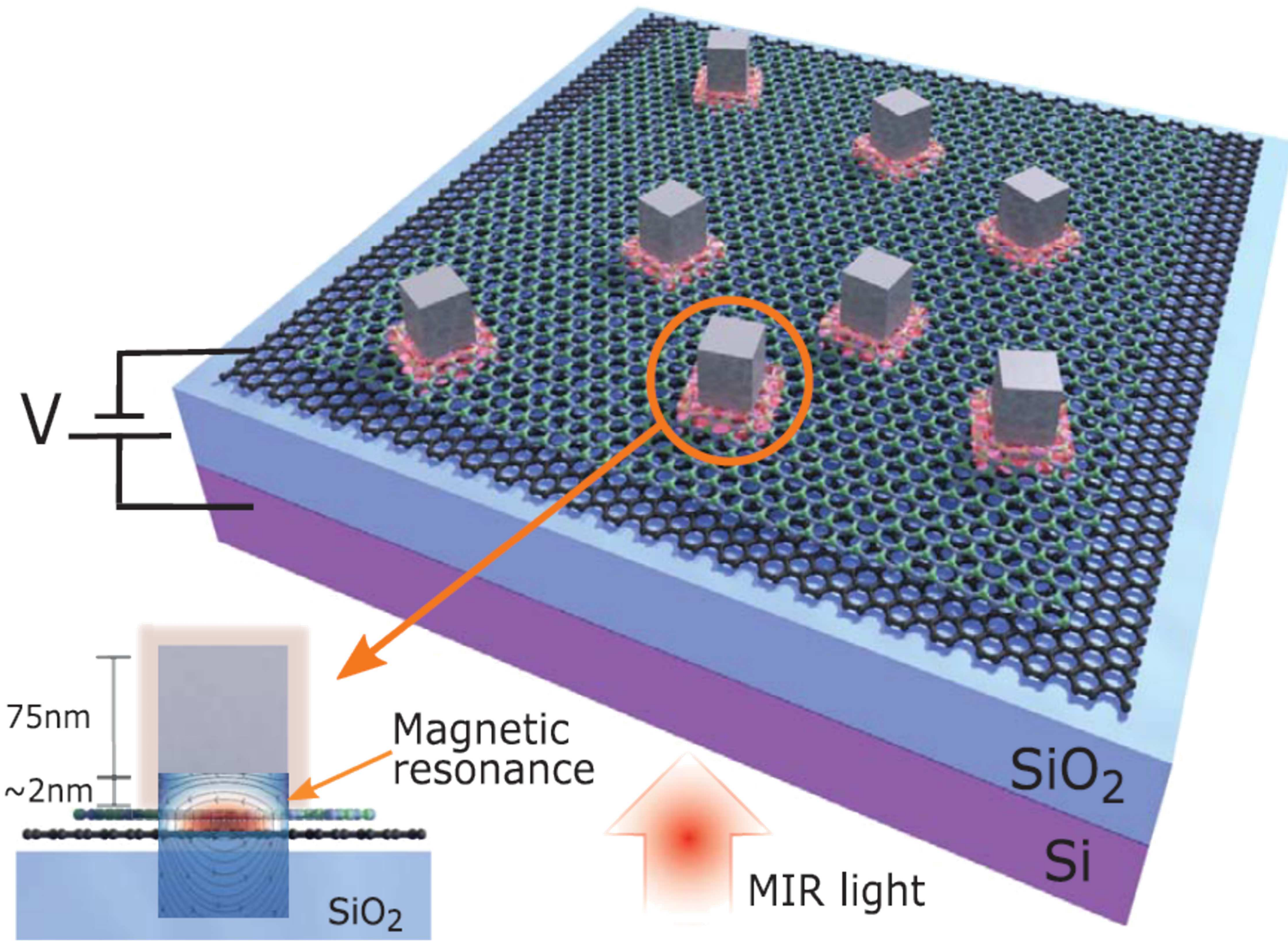


GP mode confined between the ridges:

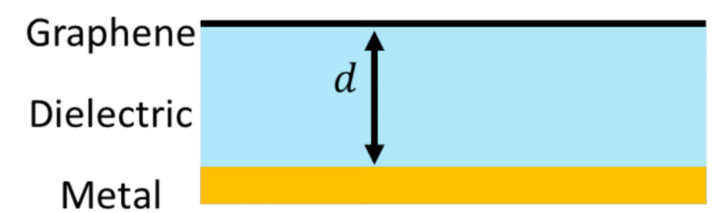
Number of electrons involved

$= \quad \cdot \quad {}^2 \quad \sim 10^2$

Increasing the confinement of light



Placing graphene close to a metallic surface:
Acoustic Graphene Plasmons (AGPs)



AGPs confine light much better than regular GPs

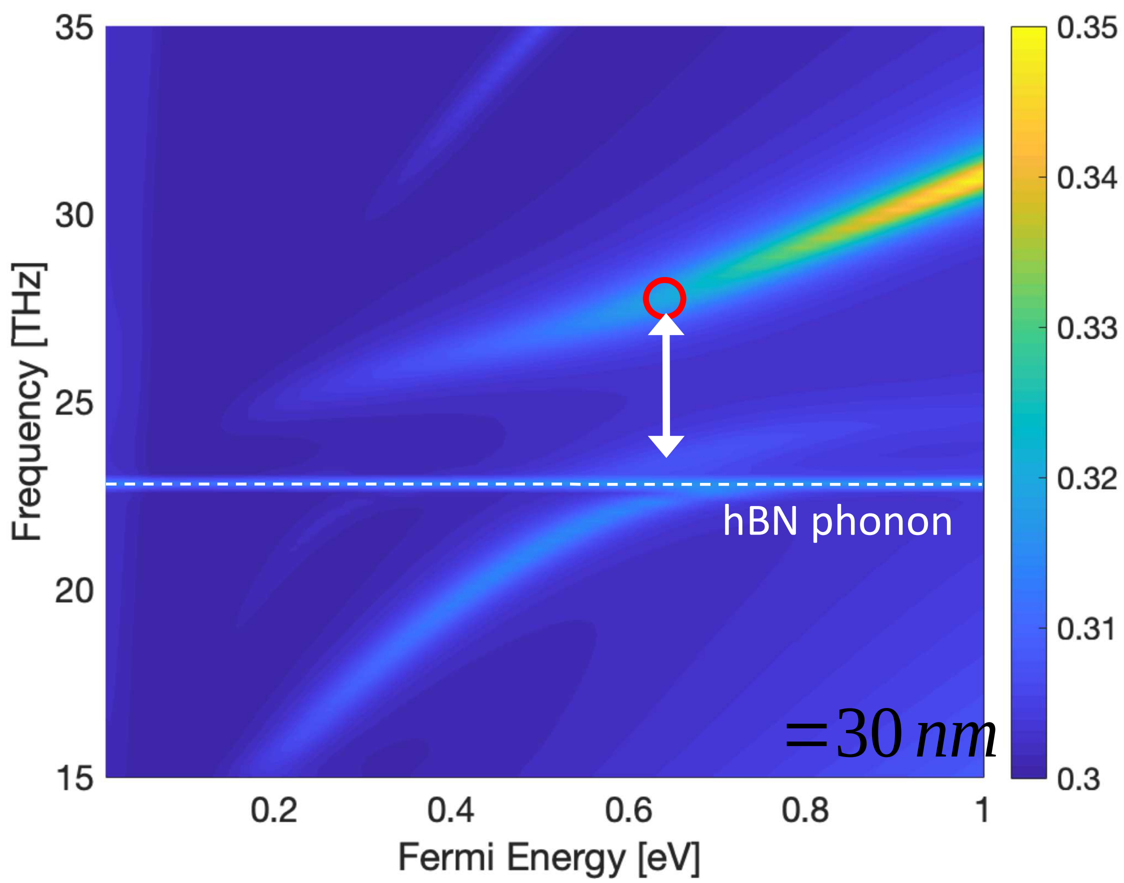
$$\sim \frac{0}{300} \sim 30 - 50\, nm \Rightarrow \frac{}{} \sim$$

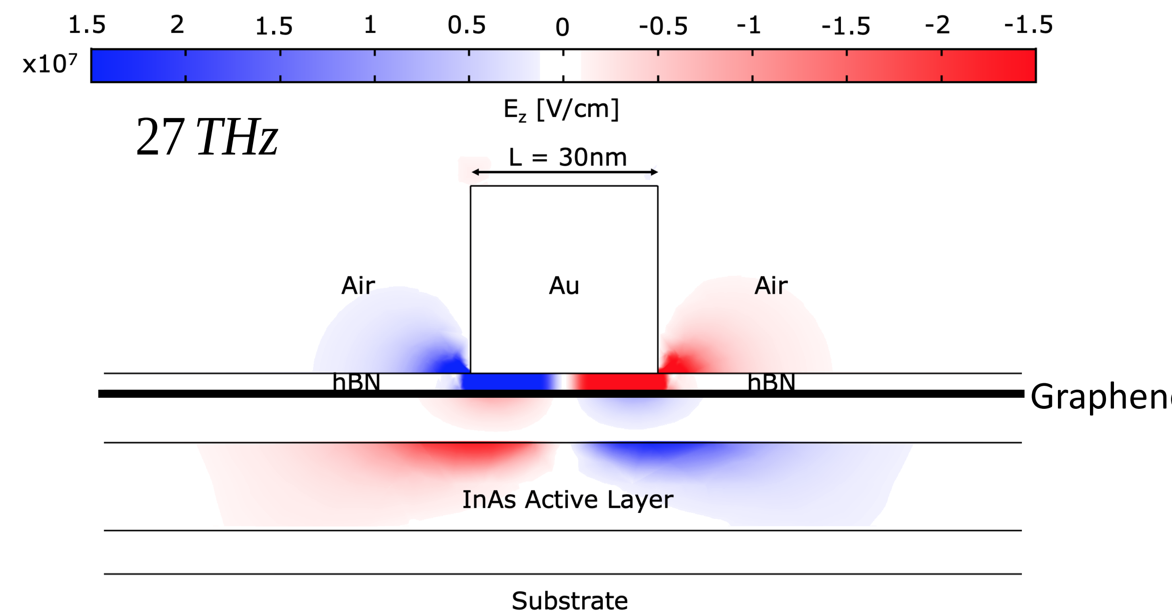
Recently measured:
far-field excitation of AGPs below metallic nanocubes randomly deposited on graphene-hBN heterostructure

I. Epstein *et al*, *Science* **368,** 1219-1223 (2020)

Resonant QW: dependence on

$\Omega \sim 3\,THz$ → ~ 0.1





GP mode confined below the cube:

Number of electrons involved

$= \cdot {}^{2} \sim 10$

Conclusion and future experiment

The system is appealing because

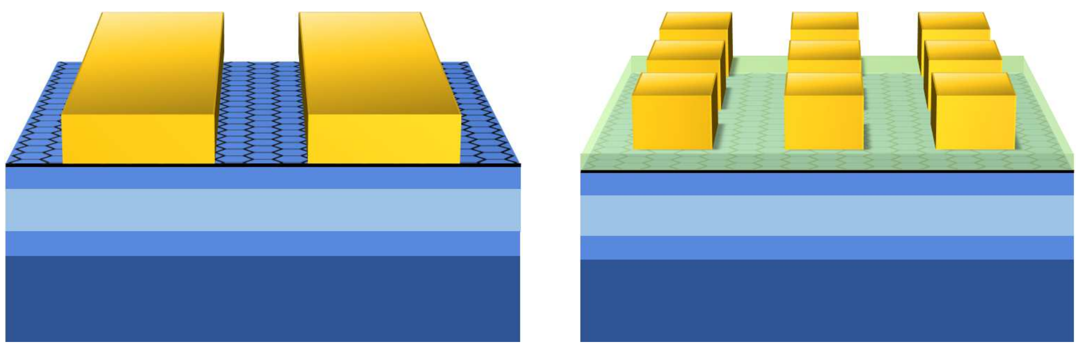
Strong coupling even in the few-electrons regime

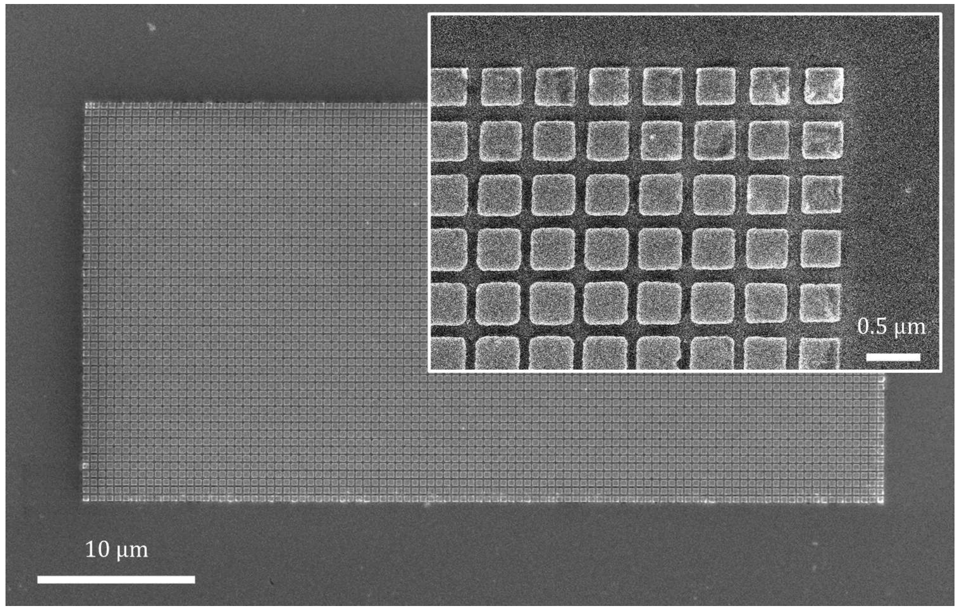
Tunable thanks to graphene

Easy to fabricate, simple far field experiment

GP structure

GPMR structure





Fabrication optimized: system will be measured soon

Dielectric may offer poor transconductance

Ionic liquids should have better performances

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G. Conte

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N. Melchioni

Thank you all for the attention!

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