UNIVERSITÀ DI PISA

Emission control of Terahertz Quantum Cascade microresonators

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Pre-Thesis

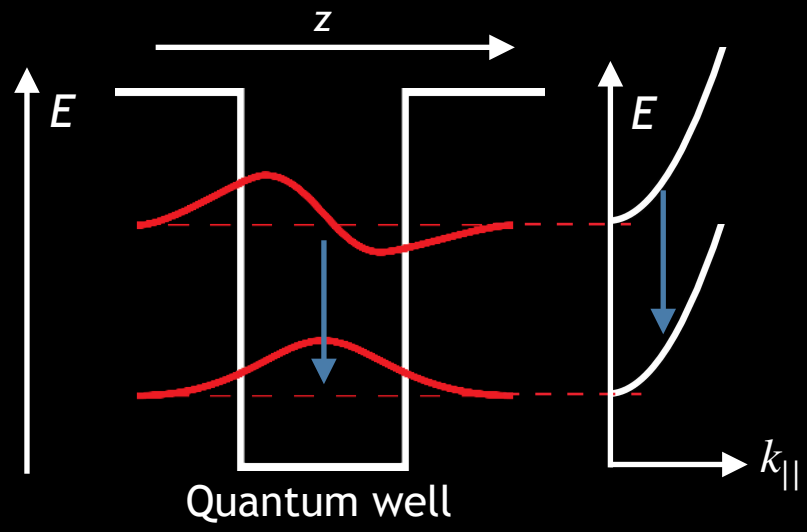
XXXII CICLO DI DOTTORATO

Dipartimento di Fisica "E. Fermi"

Introduction

Quantum Cascade Laser (QCL)

The unipolar semiconductor laser

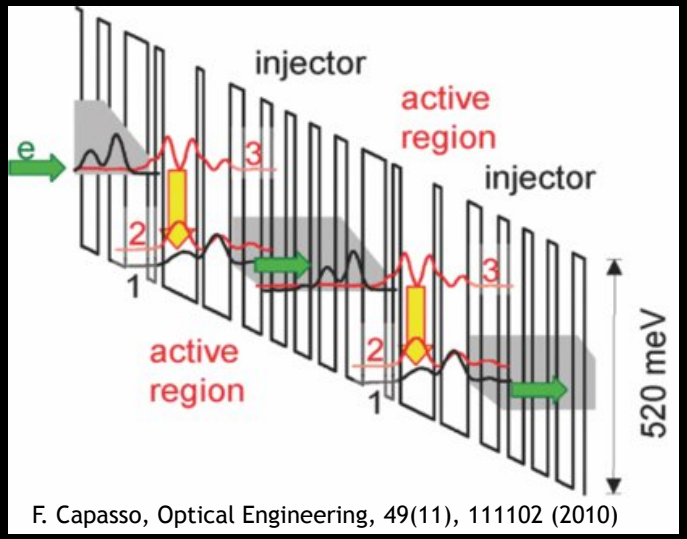


Intersubband transitions in the conduction band

"Quantum Cascade" concept

Design the width of wells and barriers

- active region (optical transition)
- injector (resonant tunneling)



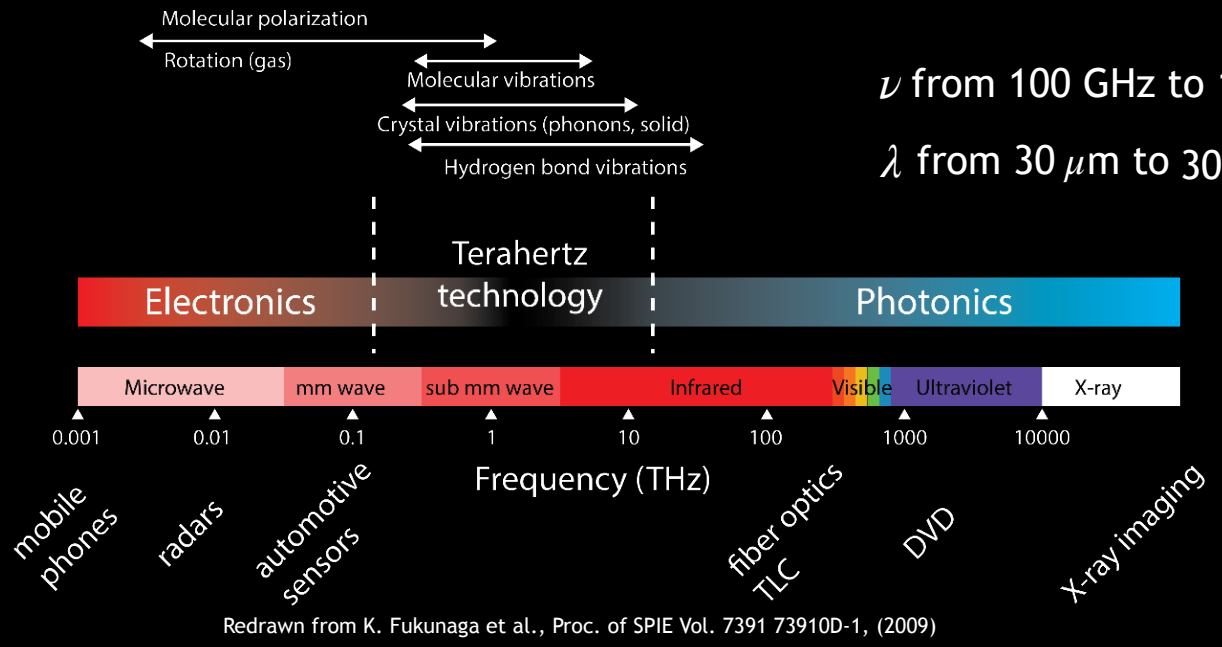
F. Capasso, Optical Engineering, 49(11), 111102 (2010)

Introduction

Terahertz (THz) radiation

1994 – Mid-IR QCL demonstration (J. Faist, F. Capasso et al., Science 264, 553)

2002 – Quantum Cascade Lasers in the THz range (R. Köhler, **A. Tredicucci** et al., Nature 417, 156)



ν from 100 GHz to 10 THz

λ from 30 μm to 3000 μm

Redrawn from K. Fukunaga et al., Proc. of SPIE Vol. 7391 73910D-1, (2009)

- Medical imaging, bio-sensing → Not invasive, sensitive to water content
- Security, Quality control → Plastic is transparent, material fingerprints
- Observational astrophysics

Introduction

THz QCL challenges

Technological challenges:

- Low-T operation due to longitudinal phonon emission (III-V, phonon energy GaAs: 36 meV) and thermal back-filling, record lasing @~200K (not considering magnetic field confinement)

- Broad-band operation for spectroscopy, small and low frequency tuneability

- Low efficiency light extraction and beam shaping

waveguide engineering

QCL miniaturization in sub-wavelength devices

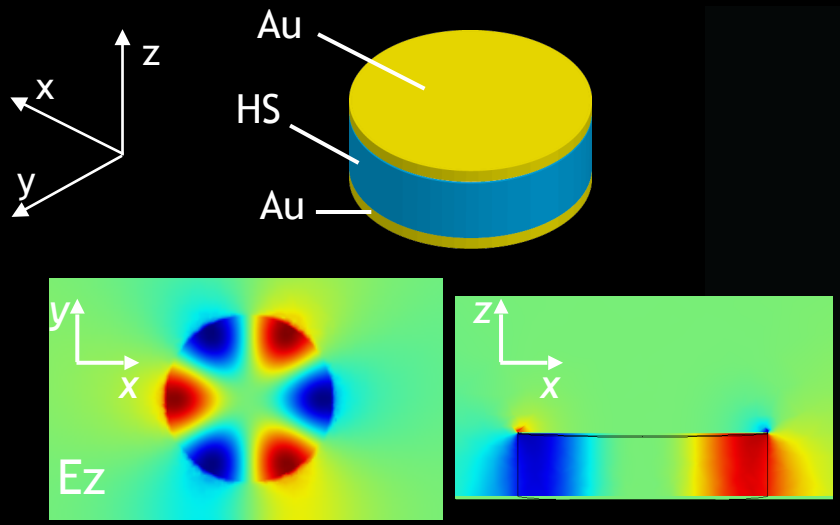
Device description

Concept

Merging features from

Photonics

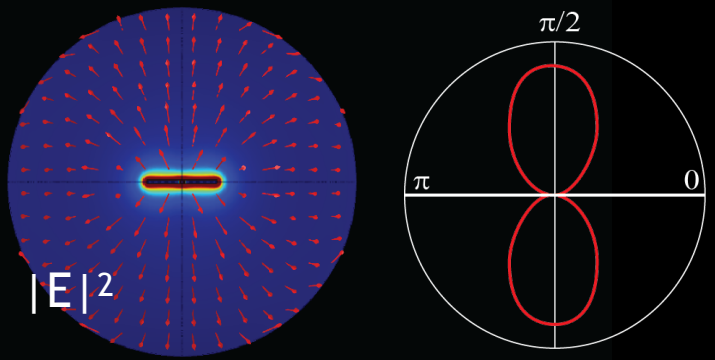
Whispering gallery mode (WGM) resonators



- High quality factors
- High confinement factor

Electronics

Dipole-antenna emitters



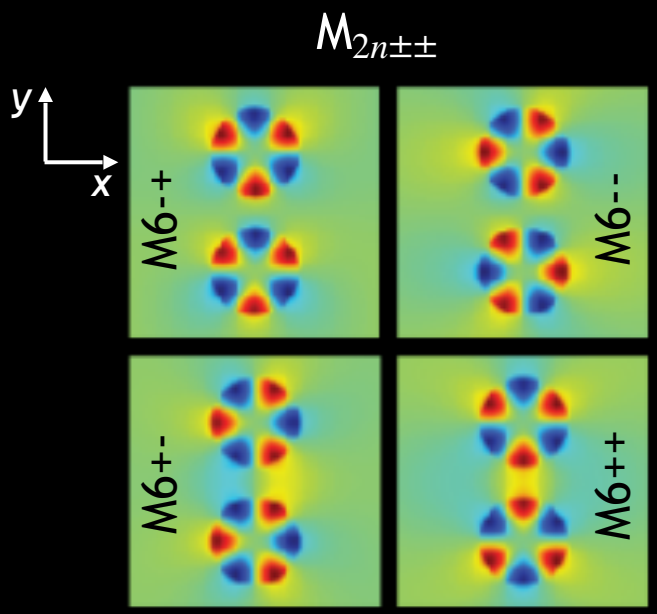
- Simple geometrical objects
- Efficient far-field coupling

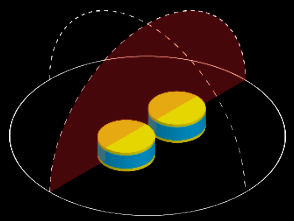
Subwavelength devices with regular vertical beam patterns

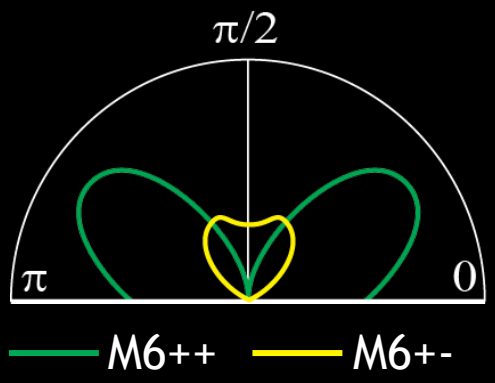
Device description

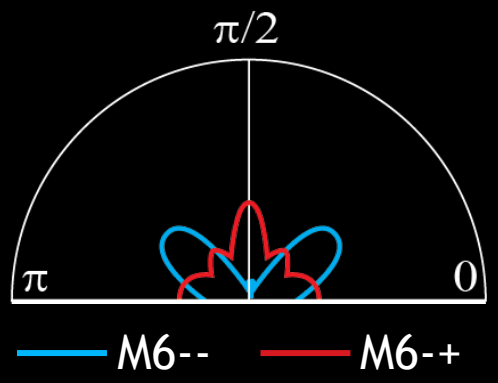
Concept

Supermodes by cavity coupling

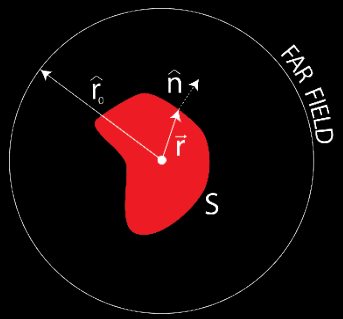








$$\vec{E}_{FF} = \frac{i\kappa}{4\pi}\hat{r}_0 \times \int \left[\vec{n} \times \vec{E} - \sqrt{\frac{\mu_0}{\epsilon_0}}\hat{r}_0 \times \left(\vec{n} \times \vec{H} \right) \right] e^{i\kappa\, \vec{r} \cdot \hat{r}_0}\, dS$$

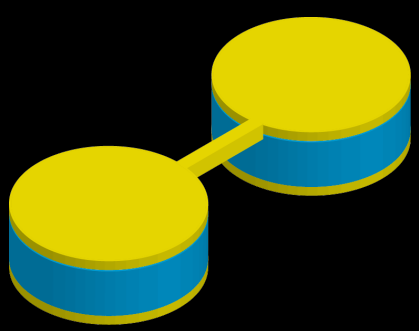


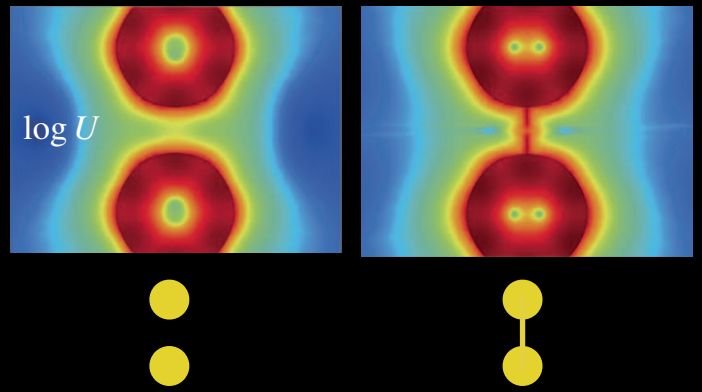
Device description

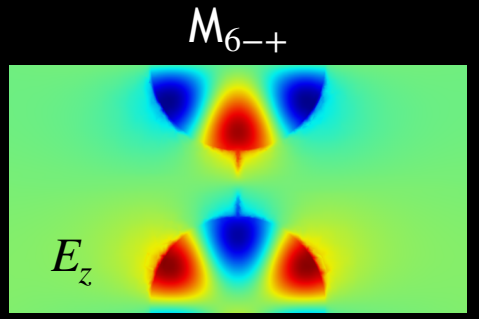
Concept

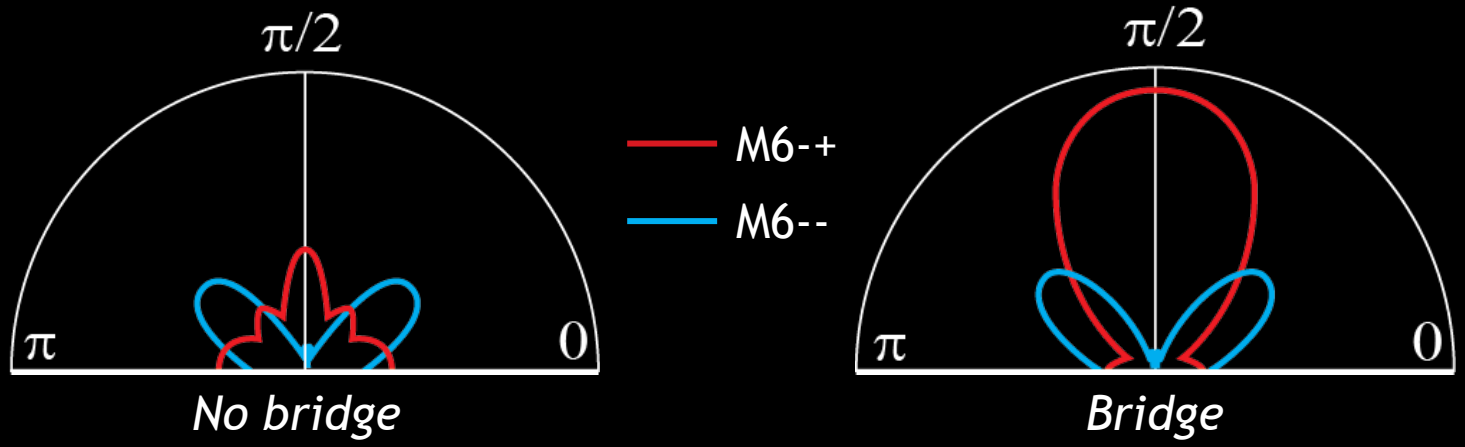
Adding a dipole antenna (suspended air-bridge wire):

Shapes the field locally like an electrical dipole





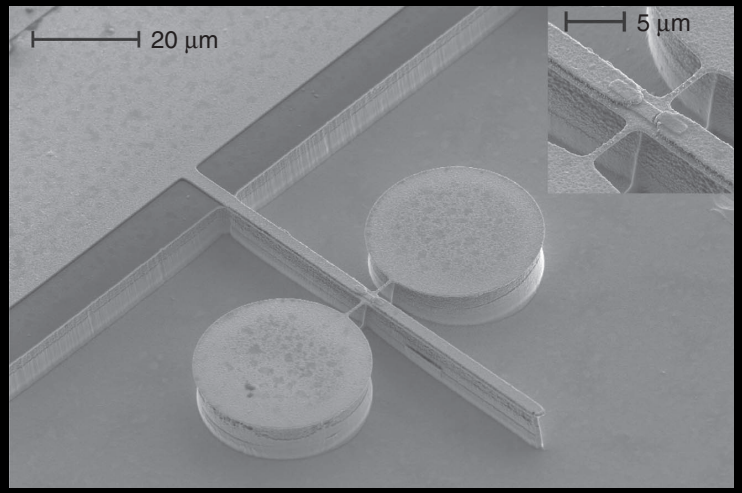


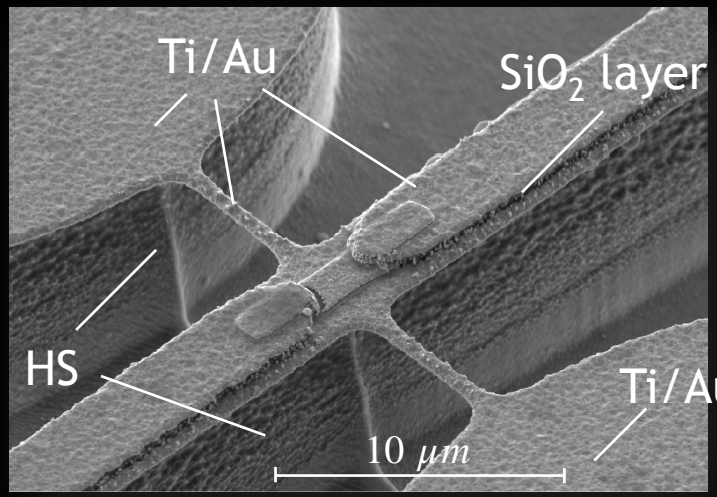


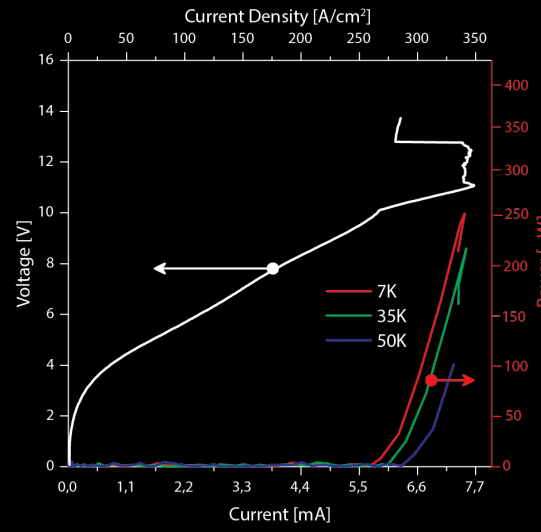
Device description

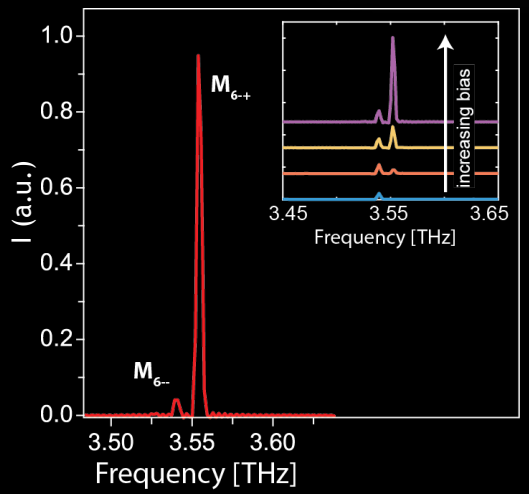
Characterization

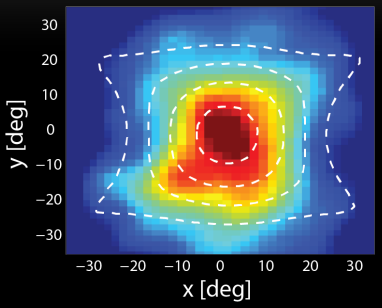
Continuous wave laser operation of a dipole-antenna terahertz microresonator,
L. Masini, A. Pitanti, (…), A. Tredicucci, **Light: Science & Applications 6**, e17054 (2017)









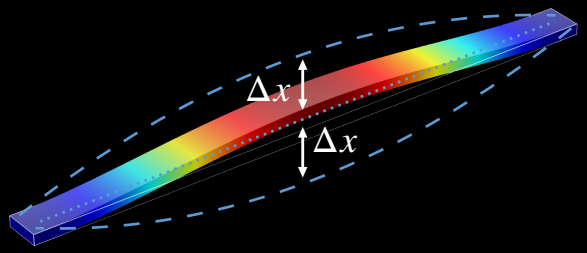


- CW-operation
- ~ 250 μW power
- < 6 mA threshold
- Vertical, regular emission

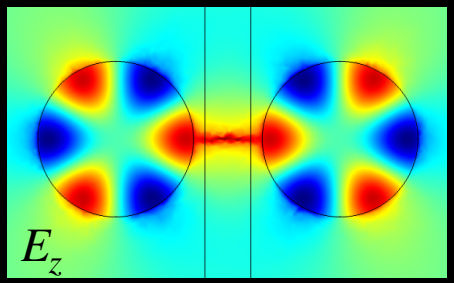
Optomechanics

Basic idea

Bridge fundamental mechanical mode

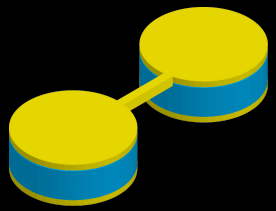


Whispering gallery mode



Radiation pressure induced OM coupling

→ Completely suspended bridge



Optomechanics

OM coupling strength

Hamiltonian formalism

$$\hat{H} = \underbrace{\hbar\omega_{\text{cav}}\,\hat{a}^\dagger\hat{a} + \hbar\Omega_{\text{m}}\,\hat{b}^\dagger\hat{b}}_{\hat{H}_0} \underbrace{- \hbar g_0\,\hat{a}^\dagger\hat{a}(\hat{b}^\dagger + \hat{b})}_{\hat{H}_{\text{int}}}$$

where $\boxed{g_0 = G\,x_{\text{ZPF}}}$ Vacuum OM coupling strength

Optical frequency shift per displacement $G = \dfrac{\partial\omega_{\text{opt}}}{\partial\Delta x}$ and $x_{\text{ZPF}} = \sqrt{\dfrac{\hbar}{2\,m_{\text{eff}}\Omega_{\text{m}}}}$ Zero point fluctuation amplitude

Finite-Element simulations

Mechanical simulation

eigenfrequency

Ω_{m}

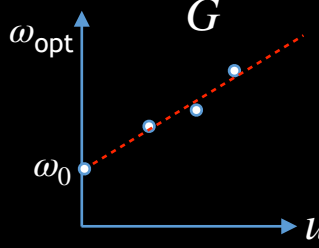
effective mass

$$m_{\text{eff}} = \rho\,\frac{\int_V |\vec{u}|^2\,dV}{\max_V |\vec{u}|^2}$$

Optical simulation

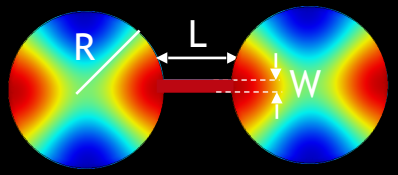
frequency shift per displacement

G

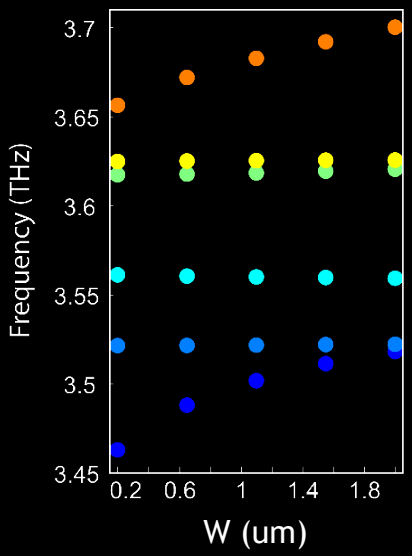


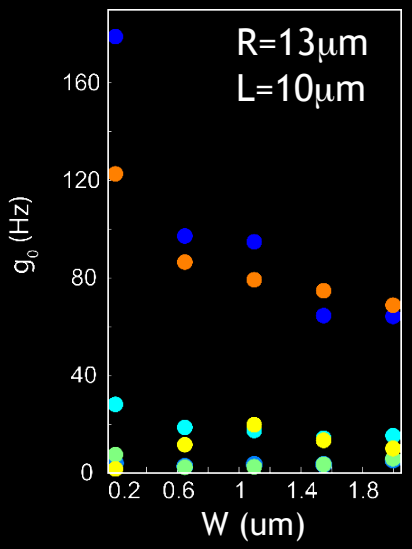
OM coupling strength for WGMs

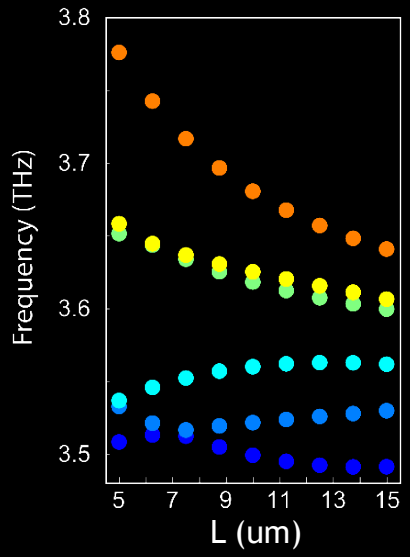
Decreasing the WGM order the OM coupling increases



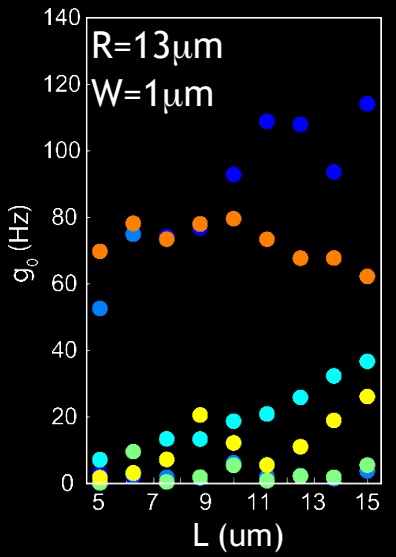
Vacuum OM coupling







Vacuum OM coupling



Single particle coupling looks low

$$g_0 \sim 100 \text{ Hz}$$

Field-enhanced OM coupling strength

$$g = g_0 \sqrt{n_c}$$

$$n_c \simeq \frac{P}{\hbar\omega_0}\tau_{\text{rad}} = \frac{P}{\hbar\omega_0}\frac{Q_{\text{rad}}}{\omega_0} \sim 10^8 \longrightarrow g \simeq 60 \text{ kHz}$$

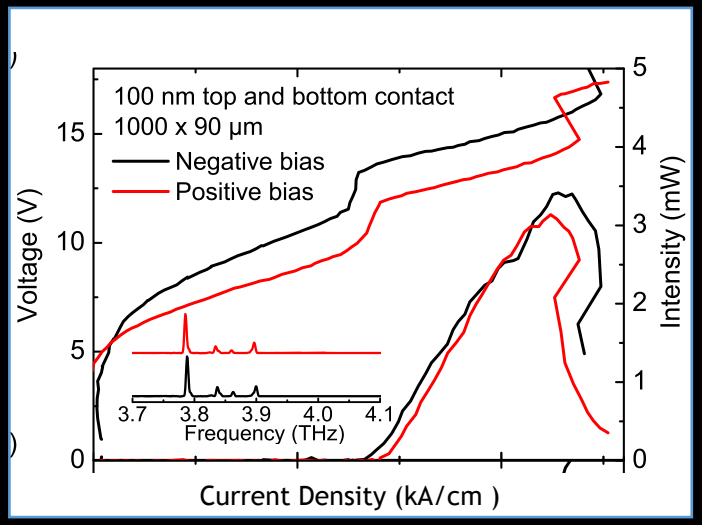
$$> 100\ \Delta\lambda$$

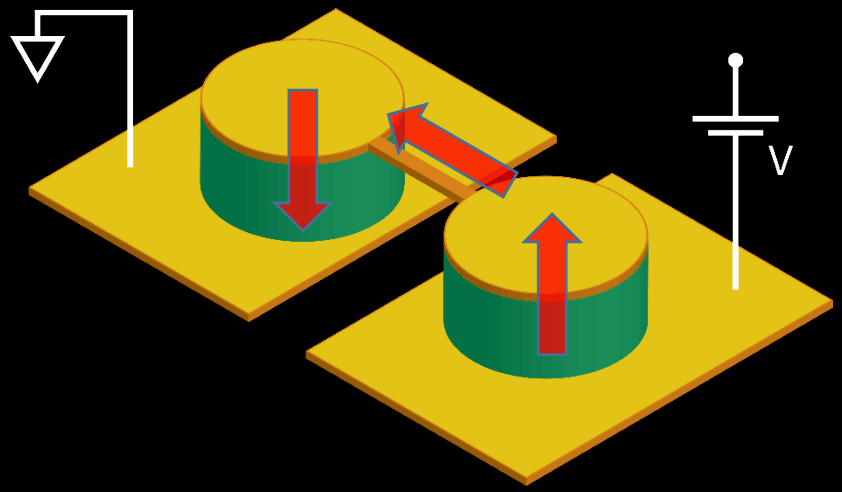
Dynamic frequency tuning at $\Omega_m \sim 10$ MHz

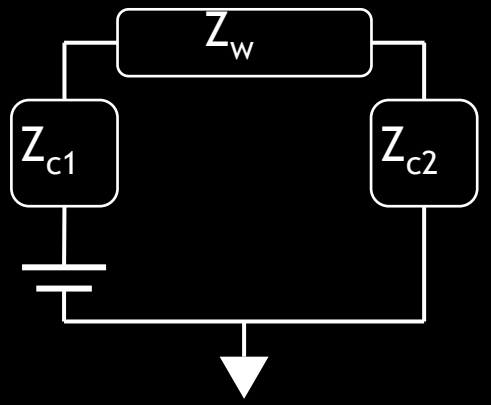
→ Symmetric heterostructure

3-QW LO phonon depletion active region
(GaAs/Al0.15Ga0.85As heterostructure)

M. Brandstetter et al. Appl. Phys. Lett. **103**, 171113 (2013)

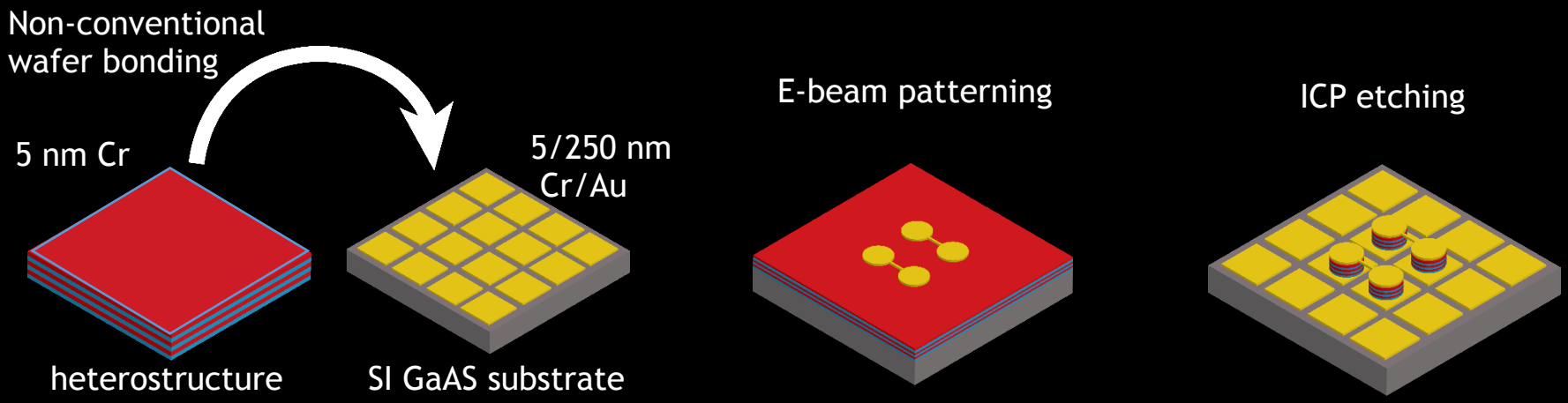


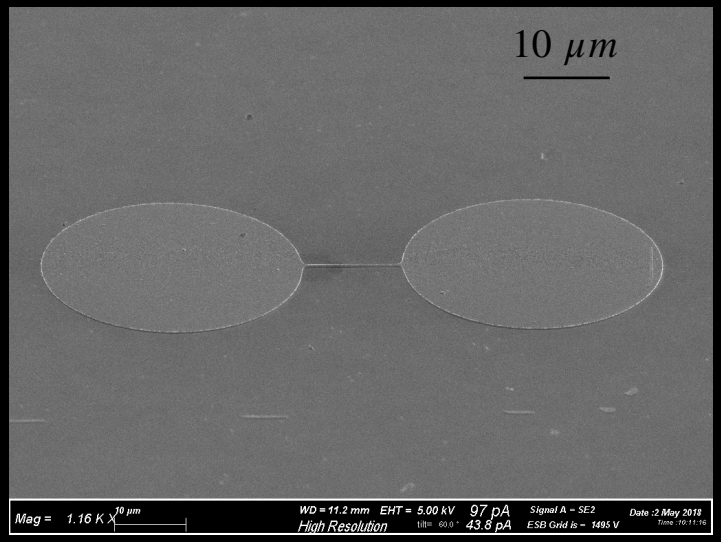


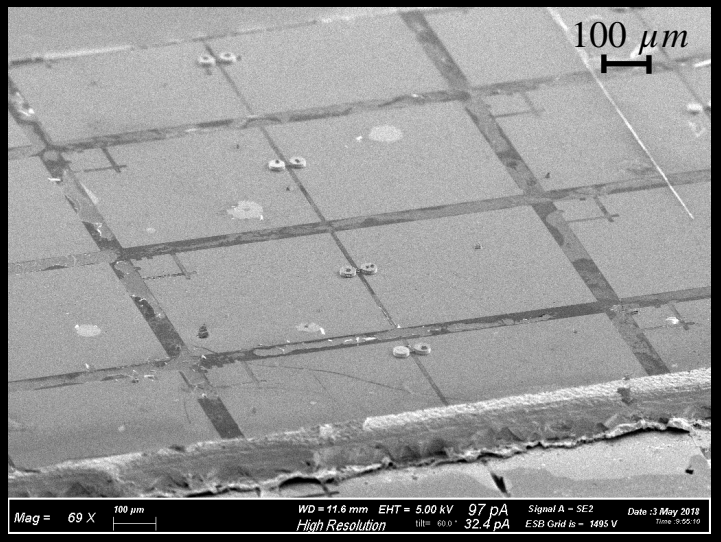


Equivalent circuit

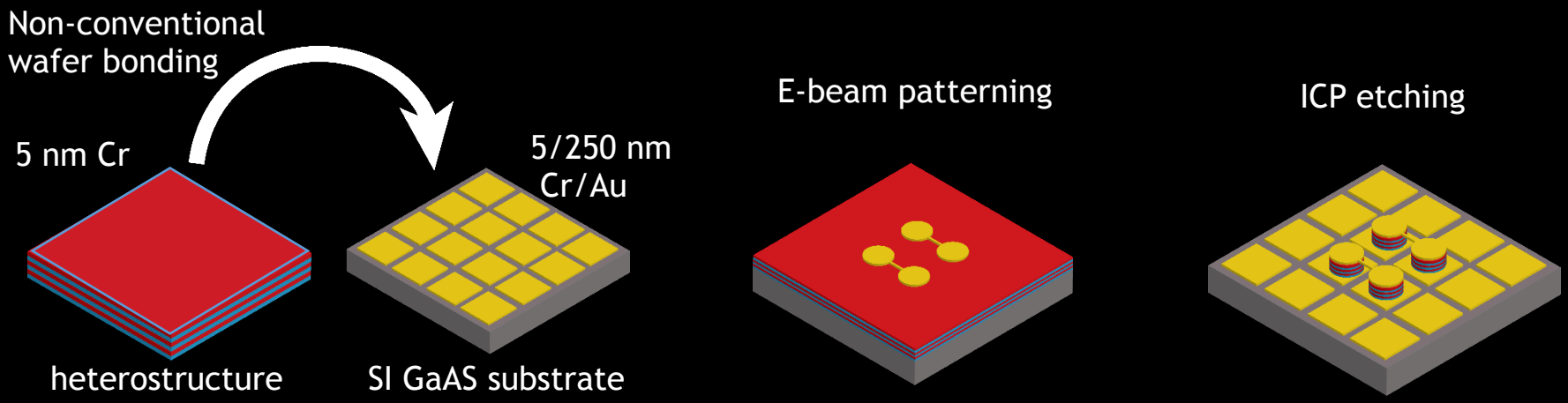
Fabrication
Procedure





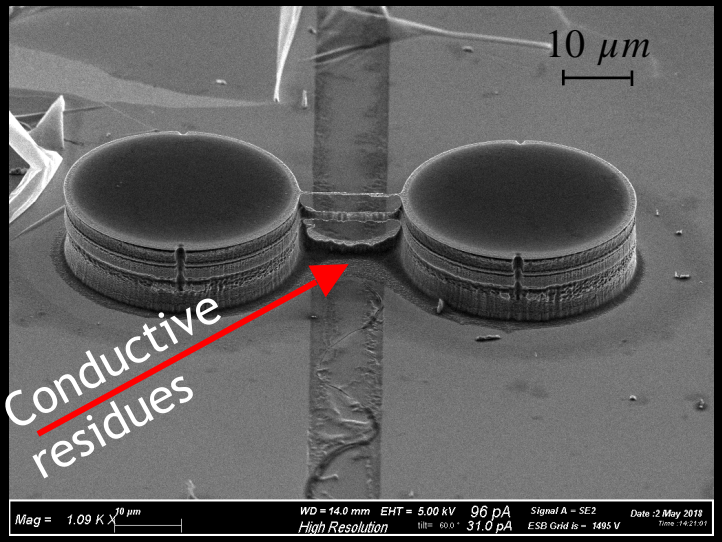


Fabrication
Procedure



Resin-based wafer bonding
on CaF2 substrates

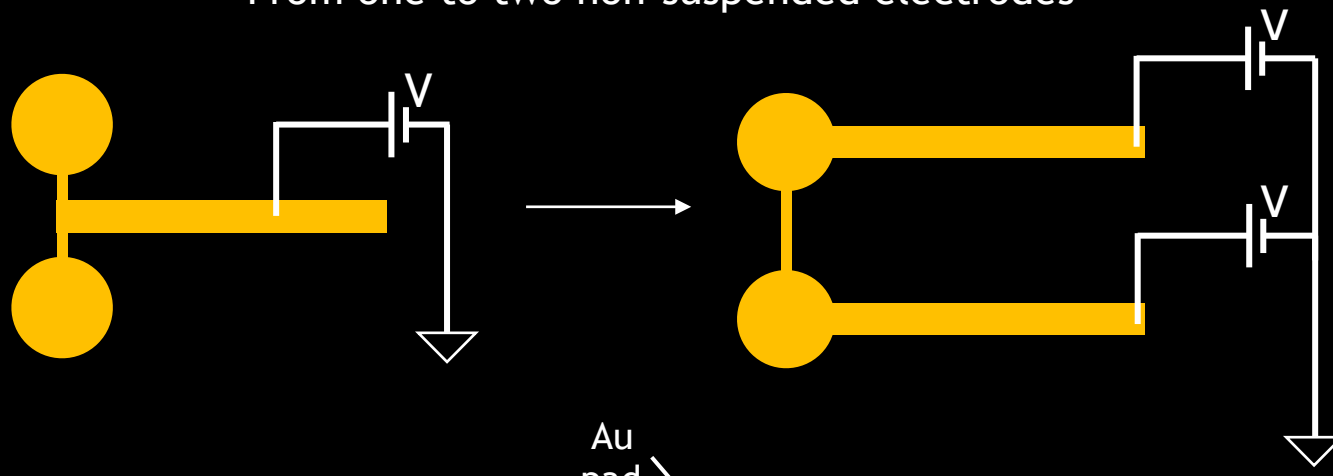
(R. Colombelli, University Paris VII)



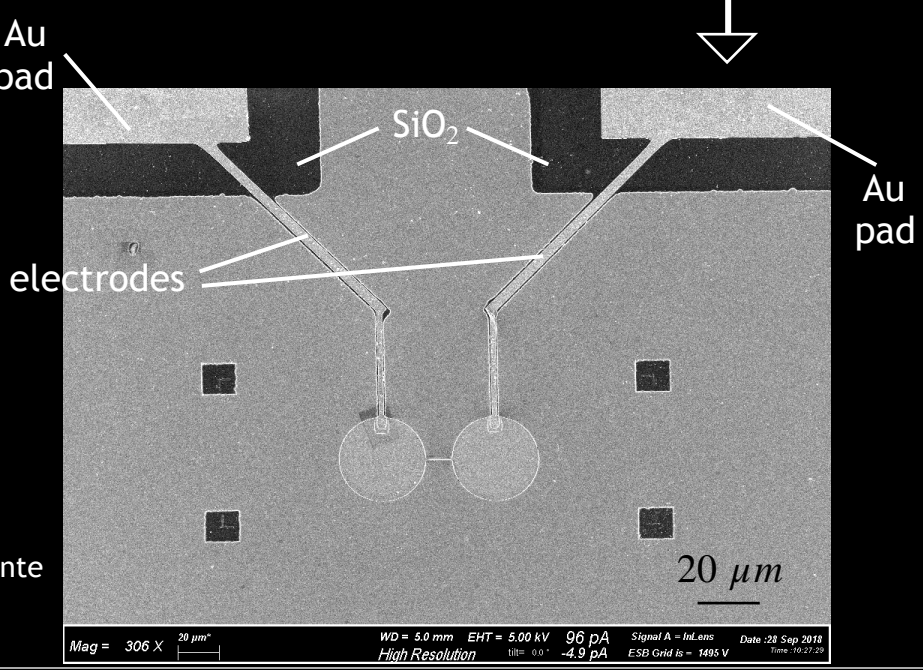
Injection engineering

Double-injection scheme

From one to two non-suspended electrodes



- Standard heterostructure (standard waferbonding)
- Additional tuning knob to control single disk emission

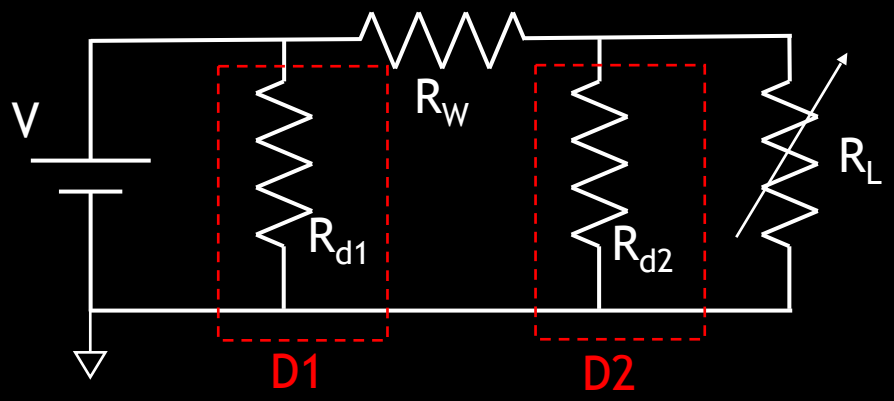


Collaboration with G.Conte

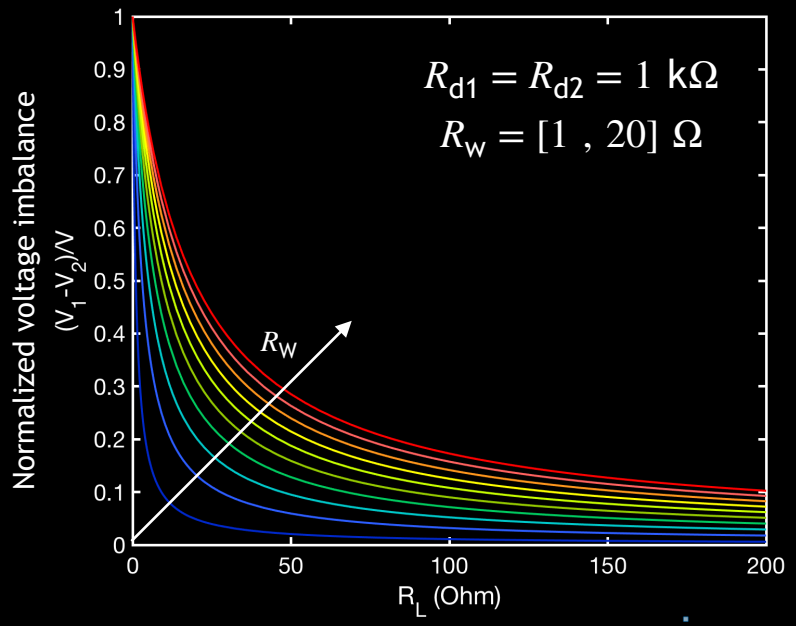
Injection engineering

Double-injection scheme

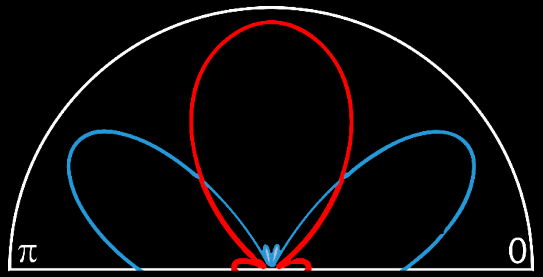
Pumping one disk and closing the other on a tunable load R_L



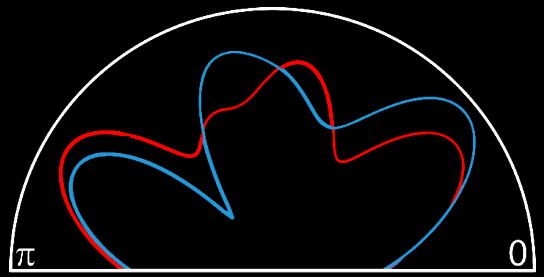
Varying the R_w/R_L ratio
the pumping of each disk is controlled



Both over lasing threshold



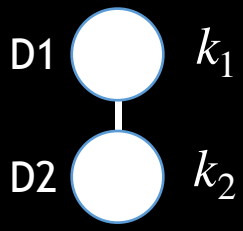
D1 over lasing threshold, D2 “cold”



Injection engineering

FE simulations

Electrical pumping simulated through the imaginary part of the disk refractive index



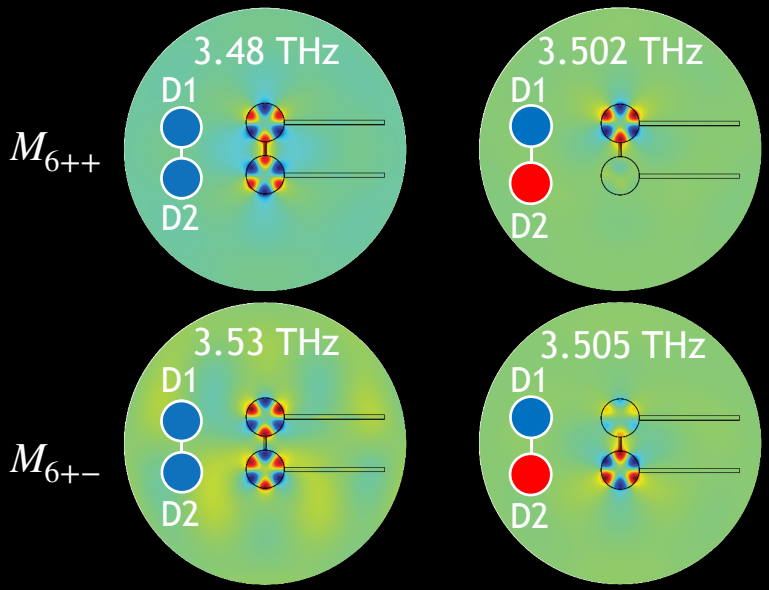
$k > 0$ Loss

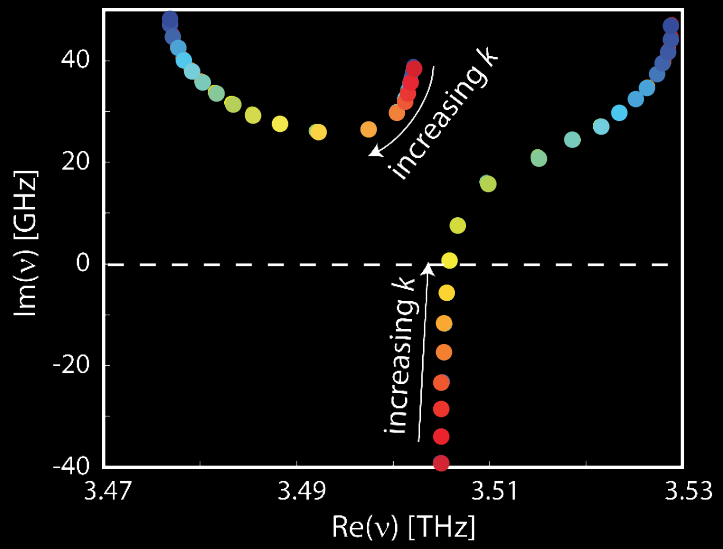
$k < 0$ Gain

Complex eigenvalues ν

$\mathrm{Im}(\nu) > 0$ not-lasing

$\mathrm{Im}(\nu) < 0$ lasing



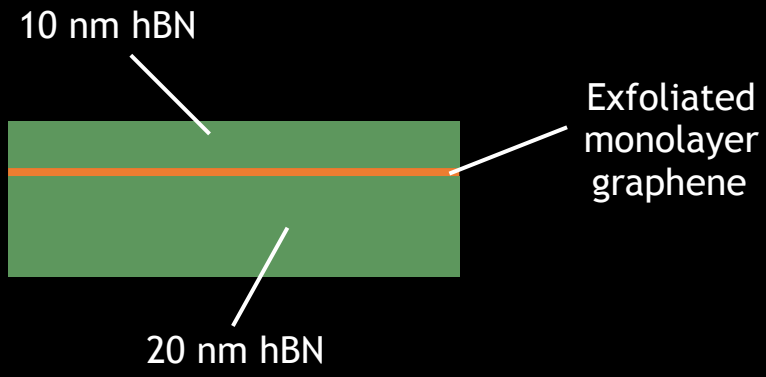


Exceptional point (EP)

Graphene-based waveguide

hBN-graphene-hBN heterostructure

Monolayer graphene incapsulated in two hexagonal boron-nitride (hBN) membranes



limited scattering from extrinsic disorder sources:

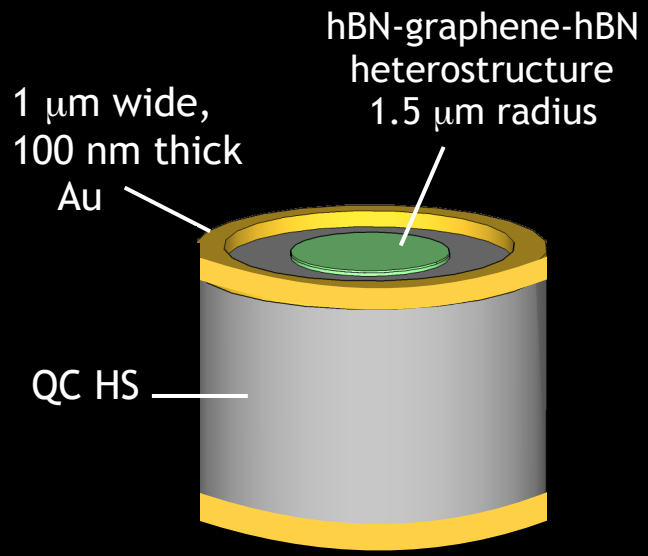
Boosted graphene electronic properties

Highly confined low-loss plasmon polaritons

*C. R. Dean, et al., Nature Nanotech. **5**, 722 (2010)*
"Boron nitride substrates for high-quality graphene electronics"

L. Wang, et al., Science 14, (2013)
"One-Dimensional Electrical Contact to a Two-Dimensional Material"

A. Woessner, et al., Nature mat. 14, (2015)
"Highly confined low-loss plasmons in graphene-boron nitride heterostructures"



Collaboration with V. Leccese

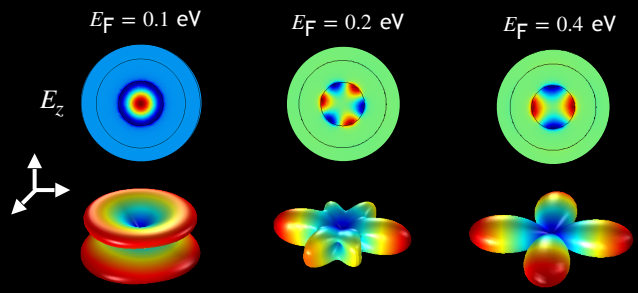
Extreme miniaturization

1) Purcell factor enhancement

$$F_P = \frac{3}{4\pi^2}\frac{\lambda_c}{n^3}^3 \frac{Q}{V_M} > 8 \times 10^5$$

→ Ultra-small threshold current

2) Electric tunability of laser emission



Conclusions and perspectives

Combining electronics and photonics new functionalities can be accessed for THz QCL:

dipole-antenna THz microresonator

- Vertical emission
- CW operation, high power
- Low-threshold, sub-wavelength dimension

Implemented functionalities

- Dynamic frequency tuning of the laser emission via optomechanical interaction

Platform for active cavity optomechanics

- Emission control (far-field and frequency) via injection engineering

Platform for laser physics around EPs

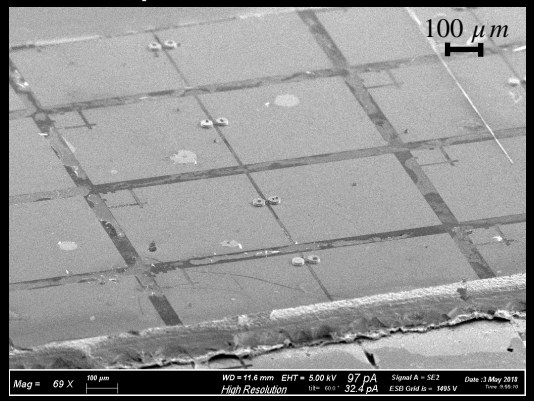
New waveguide design based on hBN-graphene-hBN heterostructure

Extreme miniaturization
Strong Purcell factor enhancement (threshold-free laser)
Emission control (far-field and frequency) by electrostatic gating

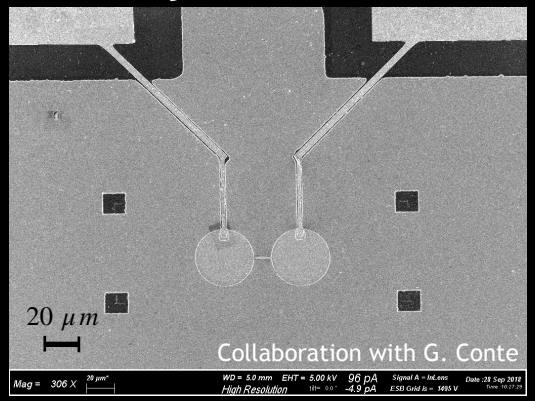
Conclusions and perspectives

Completion of devices fabrication

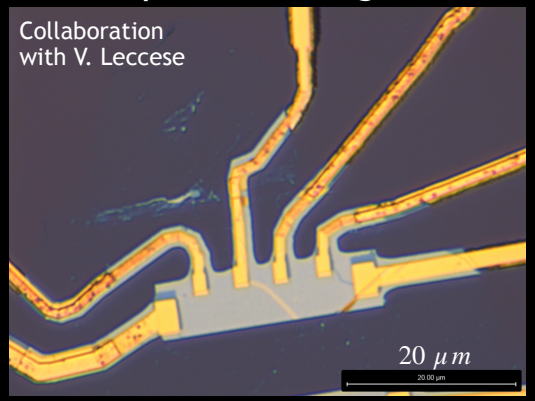
Optomechanics



Injection control



Graphene waveguide



Lasers characterization

- IVL characteristics
- Spectra
- Far-field profile

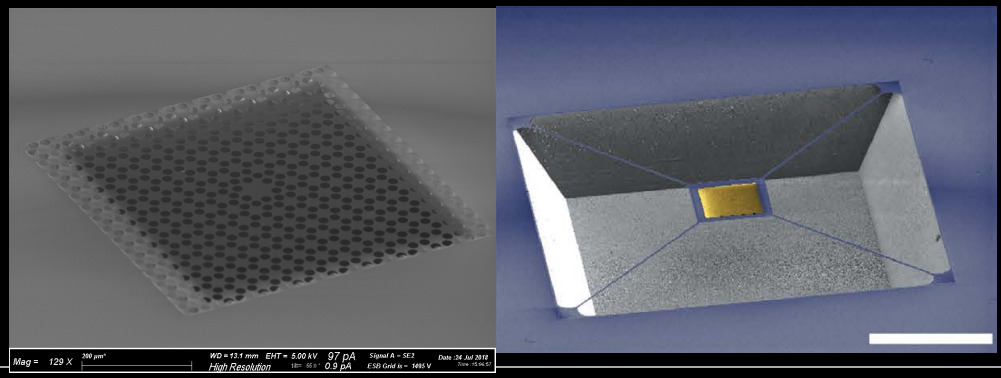
FET measurements

- Fermi energy
- Mobility

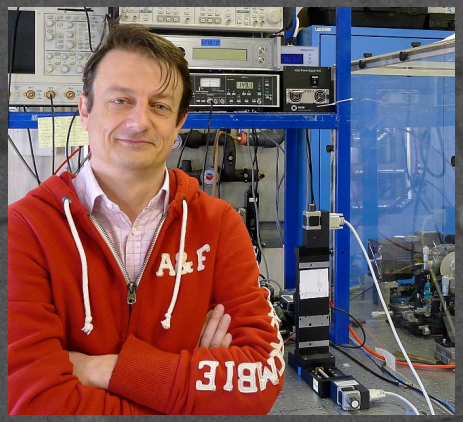
Emission control of THz QCL via external optomechanics (self-mixing technique)

Measurements next November in Leeds

Suspended SiN membranes



Acknowledgments



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Thank you for the attention