Teaching Electrons and Photons New Tricks with State-of-the art Technology: Quantum Cascade Lasers, Optical Microbilliards and QED Based Nanomechanics

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August 26, 2002 Budapest, Hu

OUTLINE

- Technologies such as MBE, Lithography, MEMS enable the design of the boundary conditions of electrons and photons in an unprecedented way

- Quantum Cascade Lasers: Quantum Design through Molecular Beam Epitaxy

  Chaotic Optical Billiards: Phase Space Design and Microlithography

  Nanomechanics based on QED (Casimir Forces): Design of Vacuum Fluctuations through MEMS

Collaborators

C. F. Gmachl, D. L. Sivco, A. Y. Cho
Bell Labs

E. Narimanov, Princeton Univ.
D. Stone, Yale Univ.

Ho Bun Chan, D. Bishop, R. Kleiman
Bell Labs

Collaborations with 10 Universities, 5 companies, 1 National Lab on applications of Quantum Cascade Lasers.

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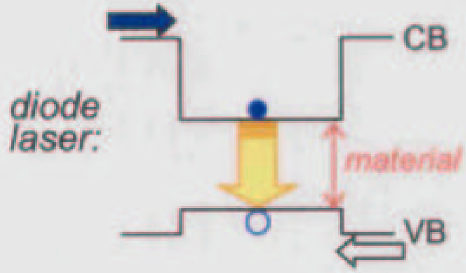
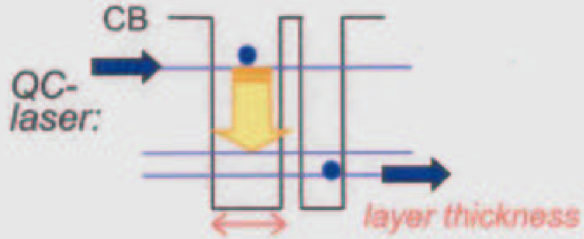
Conventional semiconductor versus QC-laser

Conventional semiconductor laser:

Light is generated across material's band-gap





1994+, QC laser; Bell Labs

QC-laser:

Light is generated across designed energy gap

"materials by design":

band structure engineering and MBE

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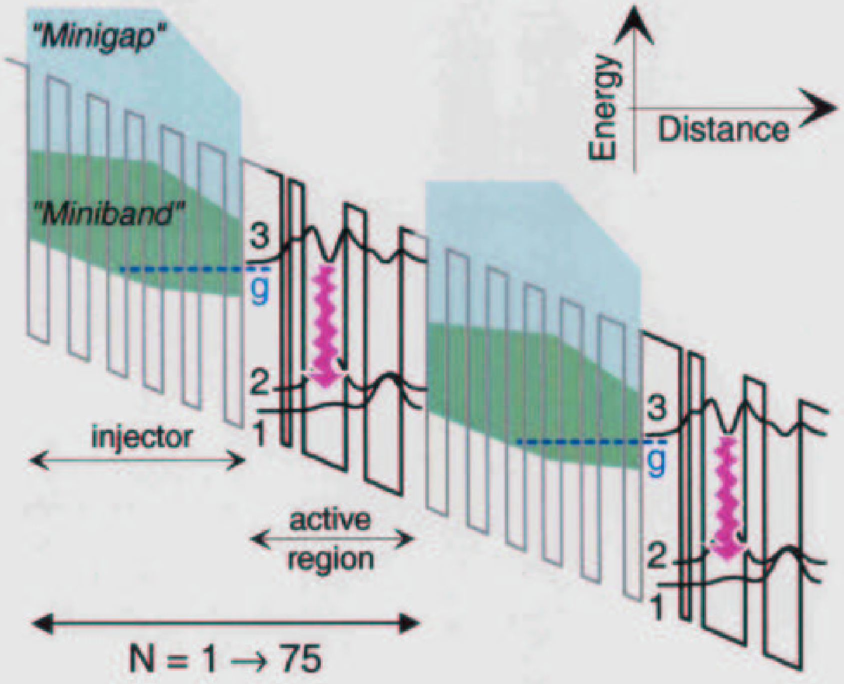
Performance highlights of QC-lasers

- Wavelength agility
  - layer thicknesses determine emission wavelength 3.5 - 70 μm
- Demonstrated applications in mid-IR gas sensing
  - reliability, reproducibility, long-term stability
- High optical power
  - cascading re-uses electrons: 2 W peak, 0.5 W cw
- Ultra-fast carrier dynamics
  - fast switching (50 ps), ultra-short pulses (3-5 ps), fast direct modulation without relaxation oscillations
- Intrinsic "design potential": e.g. multiwavelength

Unipolar Quantum Cascade Laser



- *"materials by design": using band structure engineering and MBE*
- tailor wavelength throughout mid-IR via thickness control:
  3.5 - ~~17 μm~~ 70 μm
- N (1 → 75) laser photons per injected electron through cascading:
  very high peak power: 0.5 - 1 W

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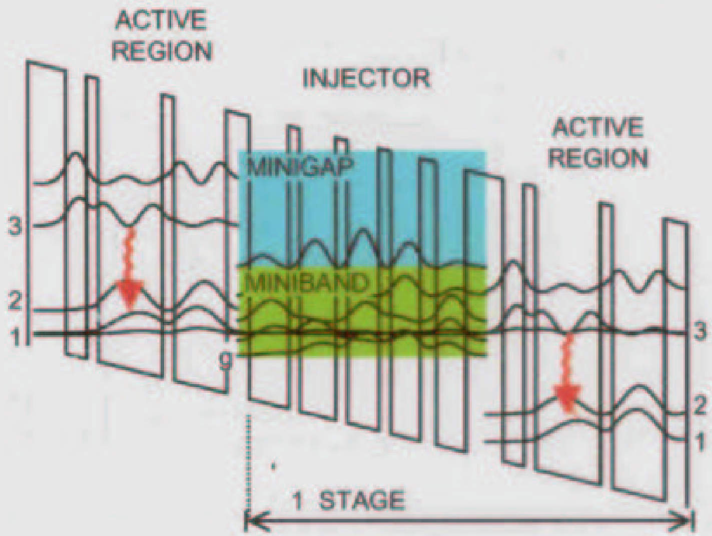
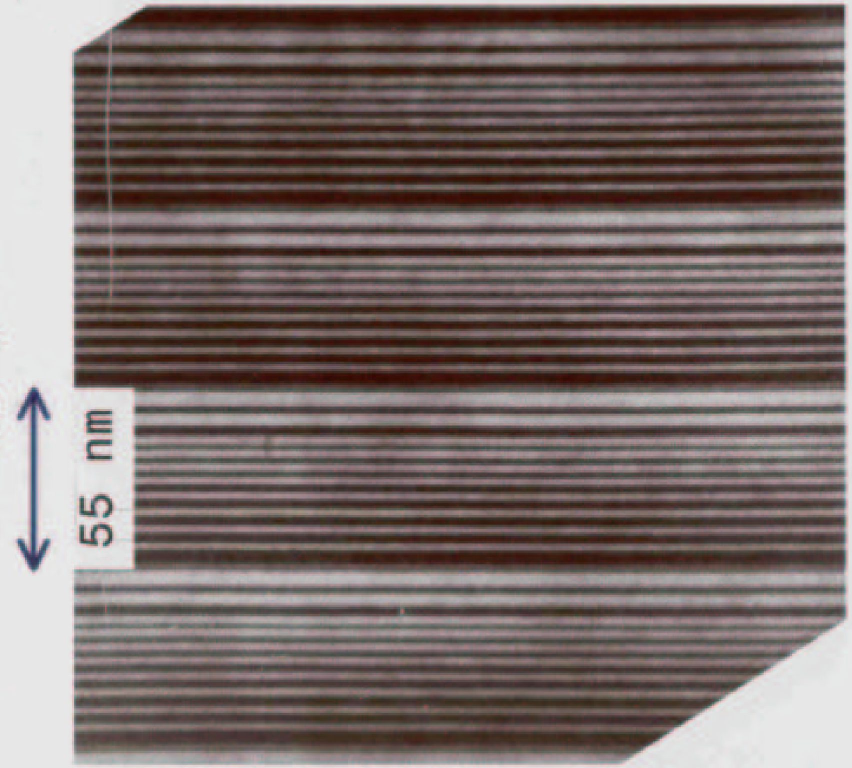
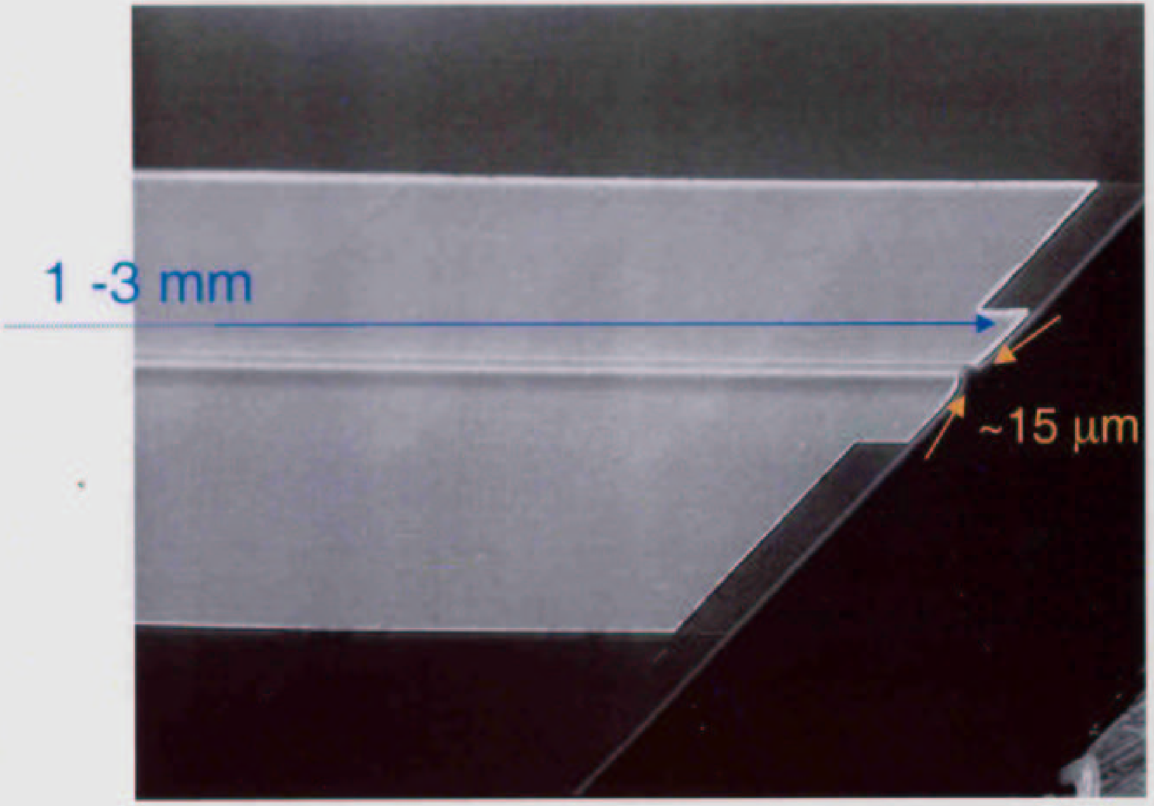
"Cascading"





- Study of QC-lasers with:
  N = 1, 3, 6, 12, 20, 30, 45, 60, 75, 100 stages
  (with approx. equal waveguide loss and device dimensions)

QC-laser photograph



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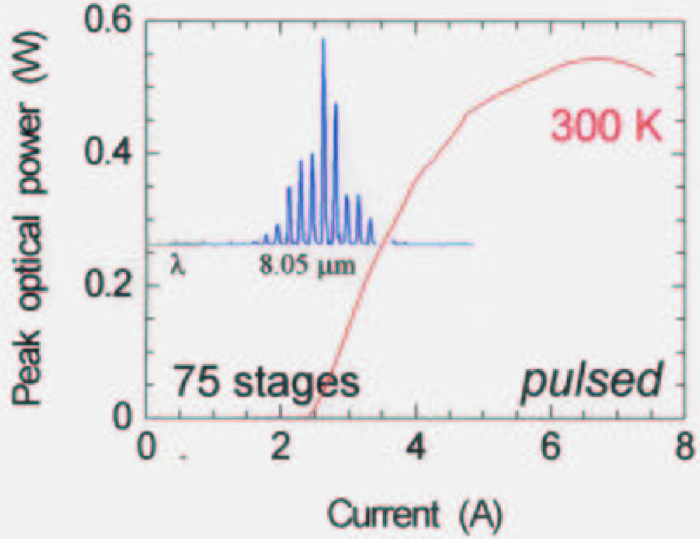
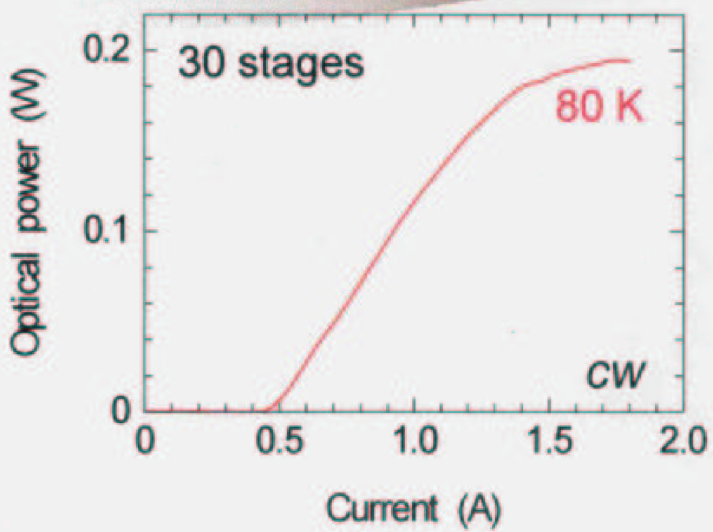
high power QC-lasers at λ ≈ 8 μm





- ~ 1000 times more powerful than commercial lead-salt lasers
  - laser lights a match easily (come, see demo in lab 7A-202)

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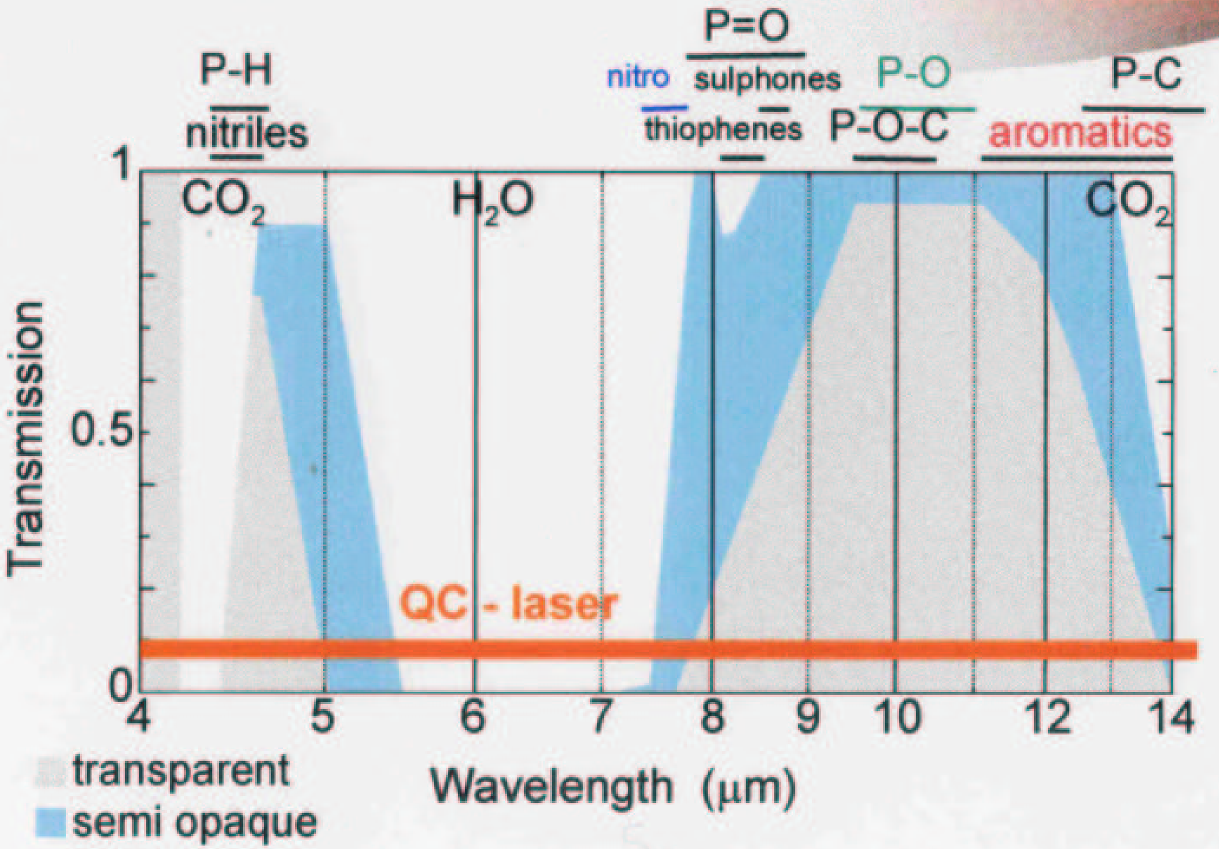
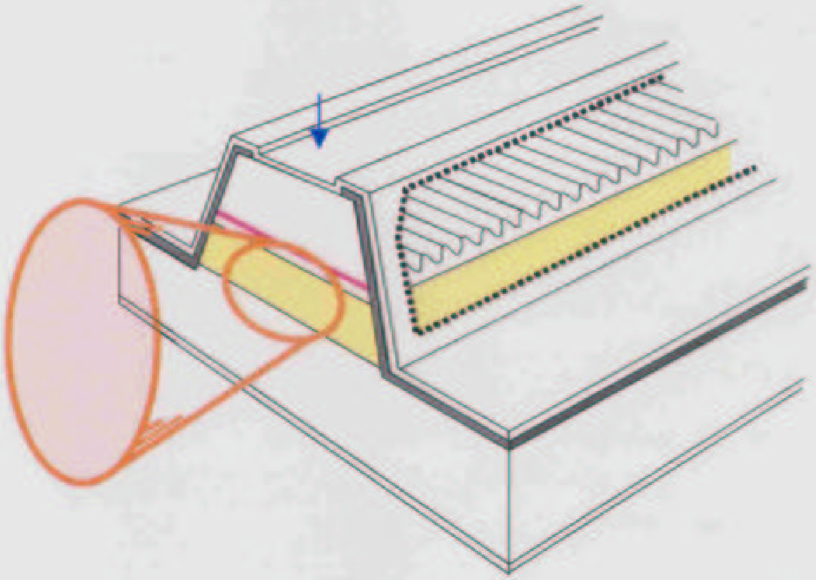
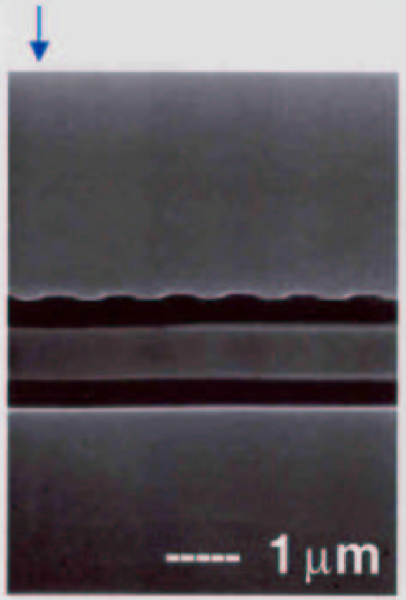
fingerprints of target gases in atmospheric windows



QC - distributed feedback laser

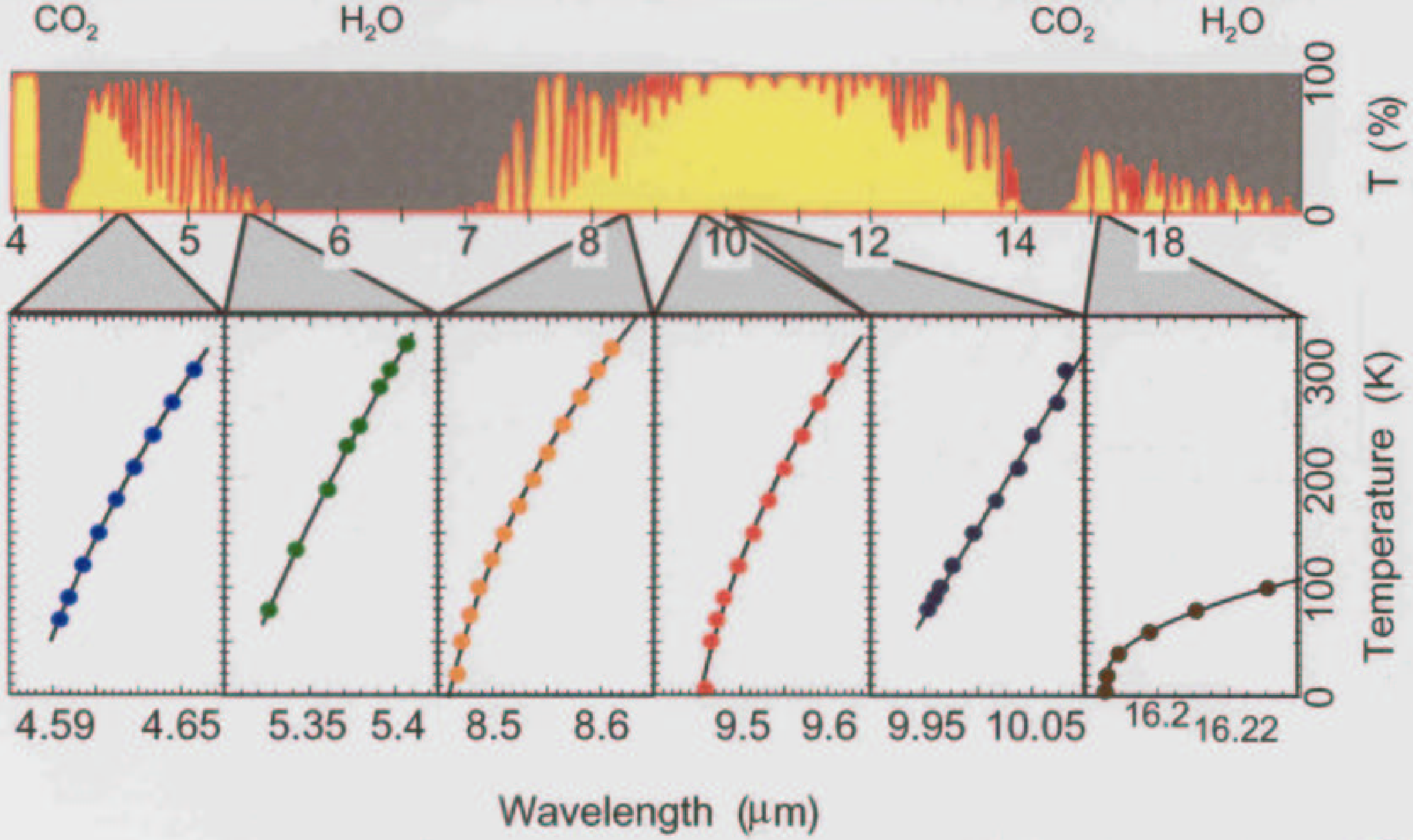




grating selects single-mode, tunable by temperature

$\lambda_{em} = 2\, n(T)\, \Lambda_{grat}$

Single-mode, tunable, mid-IR QC-DFB lasers



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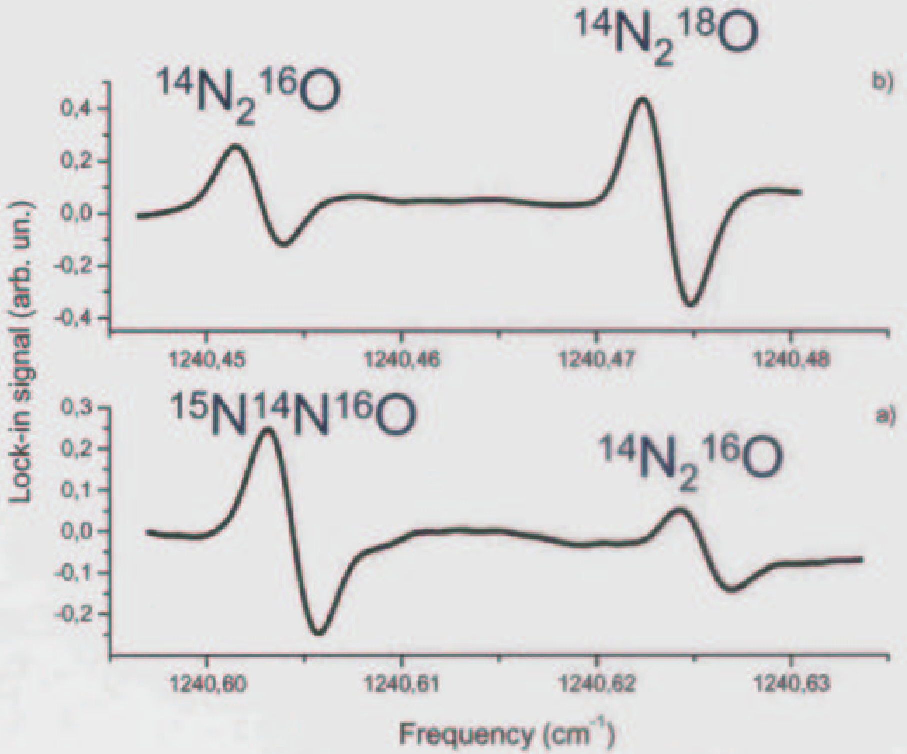
G. Gagliardi et al. “Sensitive detection of ***methane*** and ***nitrous oxide isotopes*** using a cw quantum cascade laser” *Eur. Phys. J. D* **19**, 327 – 331 (2002)



Application:
isotope detection

Laser & Method:
cw operated near 8.1 μm
wavelength modulation spectroscopy
17-cm-long sample-gas cell

Results:
detected rotational transitions of
$^{14}N_2{}^{16}O$, $^{15}N^{14}N^{16}O$, $^{14}N_2{}^{18}O$, $^{14}N_2{}^{17}O$, $^{13}CH_4$, and $^{12}CH_4$
noise-equivalent absorbance < 10^{-5} in a 1-Hz bandwidth

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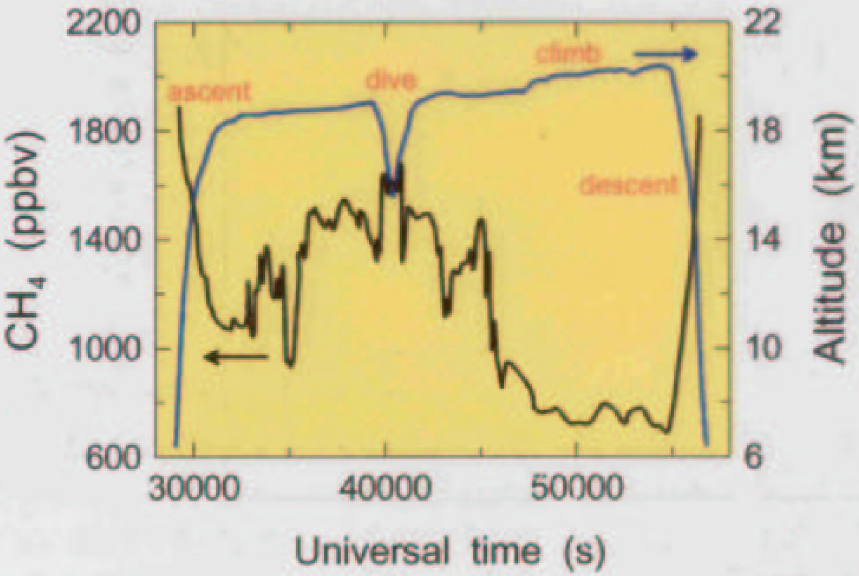
High sensitivity detection of stratospheric CH_4 and N_2O by wavelength modulation spectroscopy

collaboration with
Chris Webster et al.
NASA, JPL, and Caltech



- stratosphere over the USA and Canada, Russia and Sweden

Dryden Flight Research Center EC98-44530-3 Photographed 29APR1998
ER-2 #809 in flight (NASA photo/Jim Ross)

- reliable operation and detection over 23 days, 8 h/day - repeatedly
- detection limit: ~ 2ppbv

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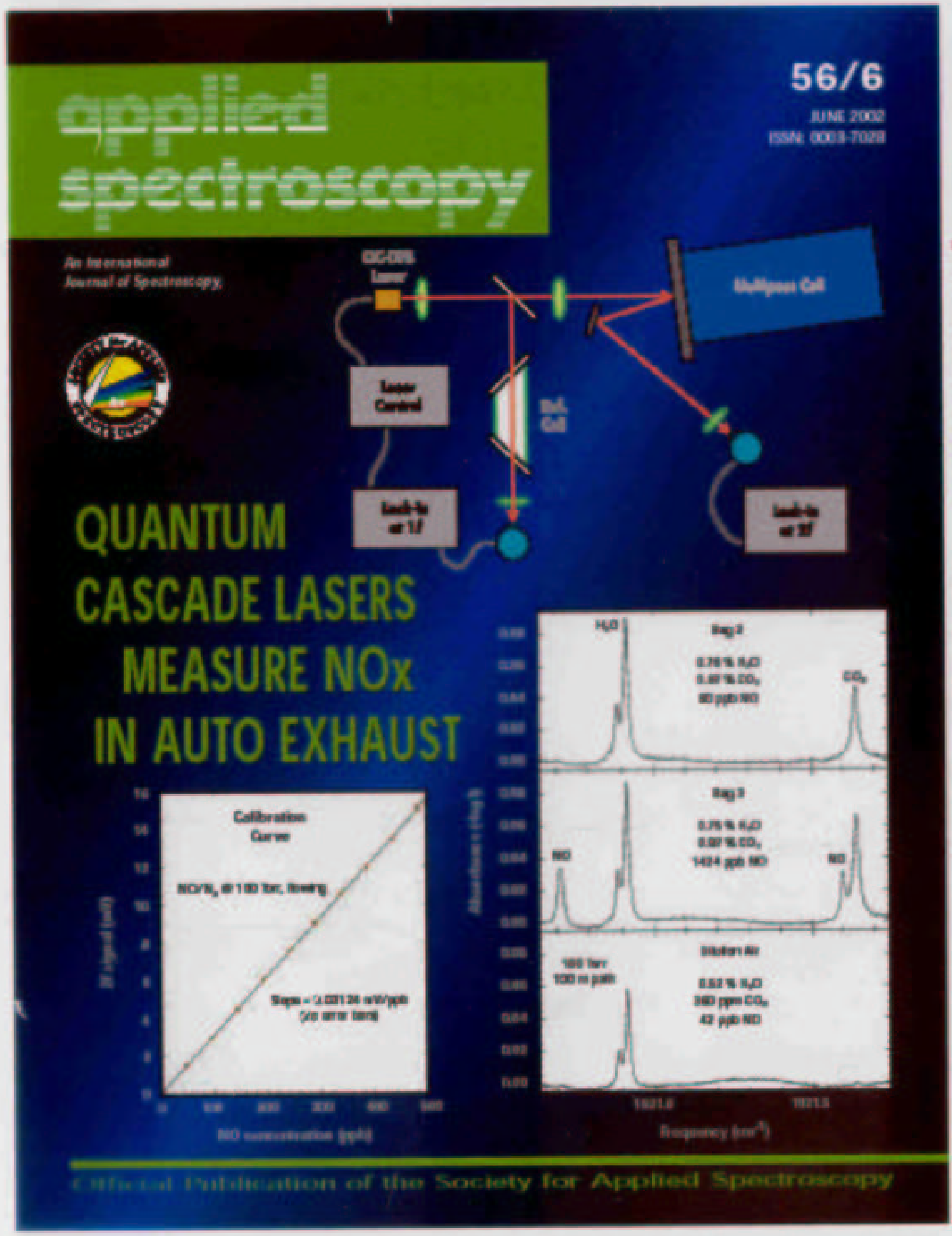

"Using a Wavelength-Modulated Quantum Cascade Laser to Measure NO Concentrations in the Parts-per-Billion Range for Vehicle Emissions Certification"

W. H. Weber, J. T. Remillard, R. E. Chase, J. F. Richert et al.

Ford Motor Company, Physics Department, Dearborn, Michigan 48121-2053 USA

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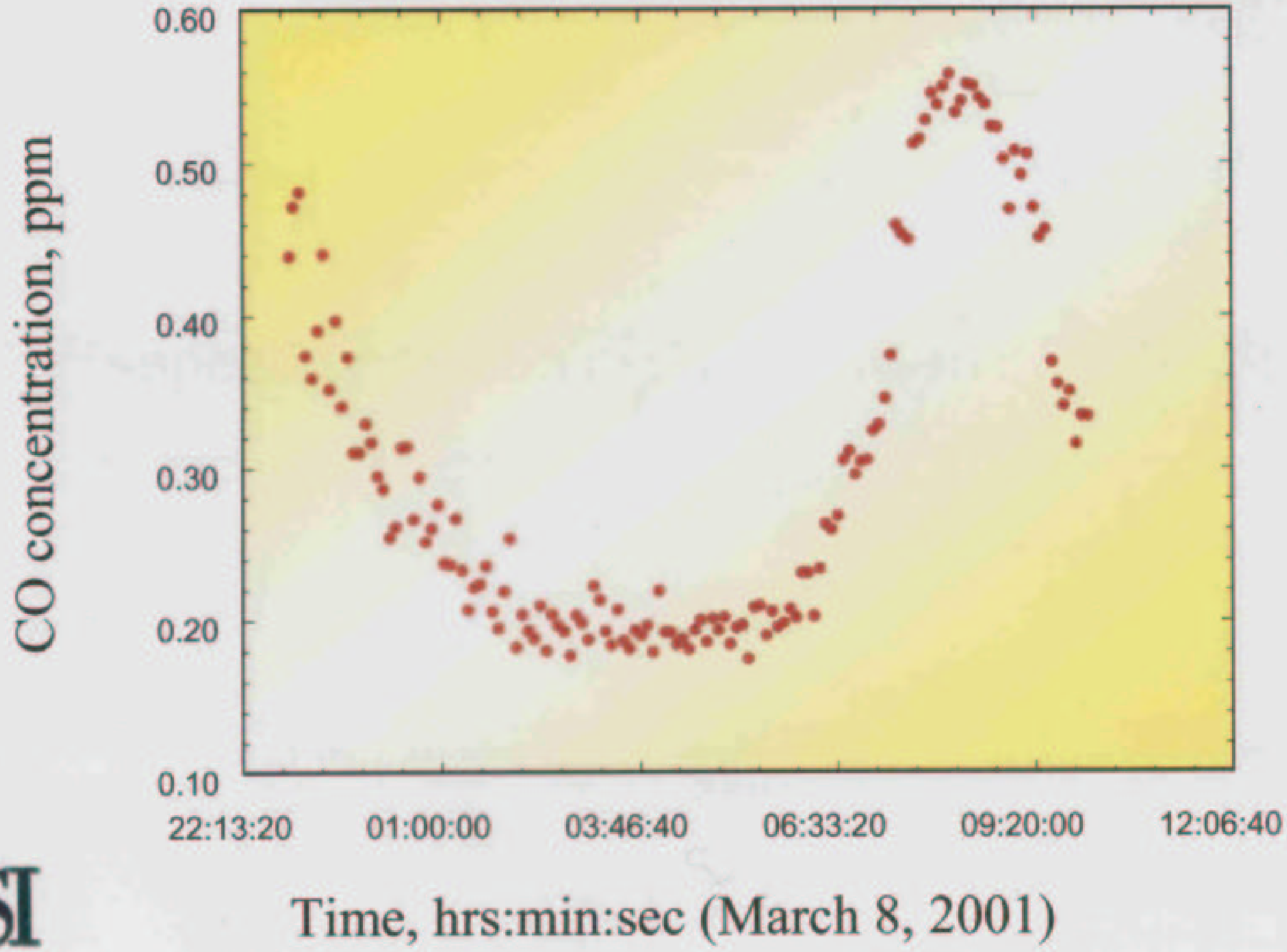
CO Concentration Measurements

Mark Allen et al. *Frank Tittel et al.*

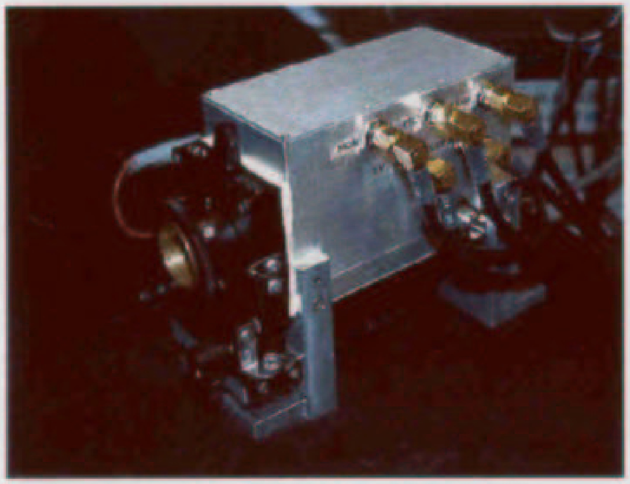


PSI

RICE

http://www.psicorp.com/html/prod/qclsensors.htm

NO- and CO-sensor products:



Sensor develoment:

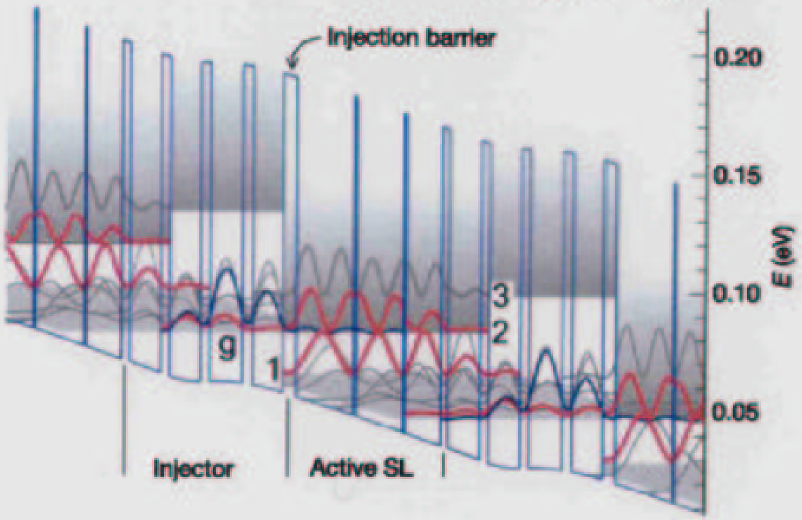
"PSI to Develop Photonic Technologies for Early Detection of Human Disease
Physical Sciences Inc. (PSI) joined by sub-contractors Los Gatos Research and Rice University, will be exploring the application of advanced, mid-IR laser technology to the early detection of human pathologies. The three-year NASA program is administered by the Fundamental Space Biology Program in cooperation with the National Institutes of Health's National Cancer Institute. ...."

Terahertz semiconductor heterostructure laser

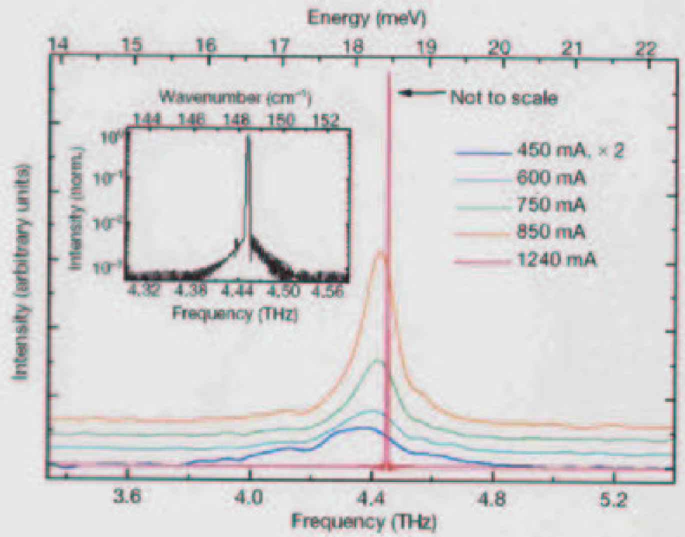
Rüdeger Köhler, Alessandro Tredicucci, Fabio Beltram, Harvey E. Beere, Edmund H. Linfield, A. Giles Davies, David A. Ritchie, Rita C. Iotti, Fausto Rossi

Nature, vol. **417**, pp. 157 - 159, May 9, 2002

Band structure, GaAs/$Al_{0.15}Ga_{0.85}As$:

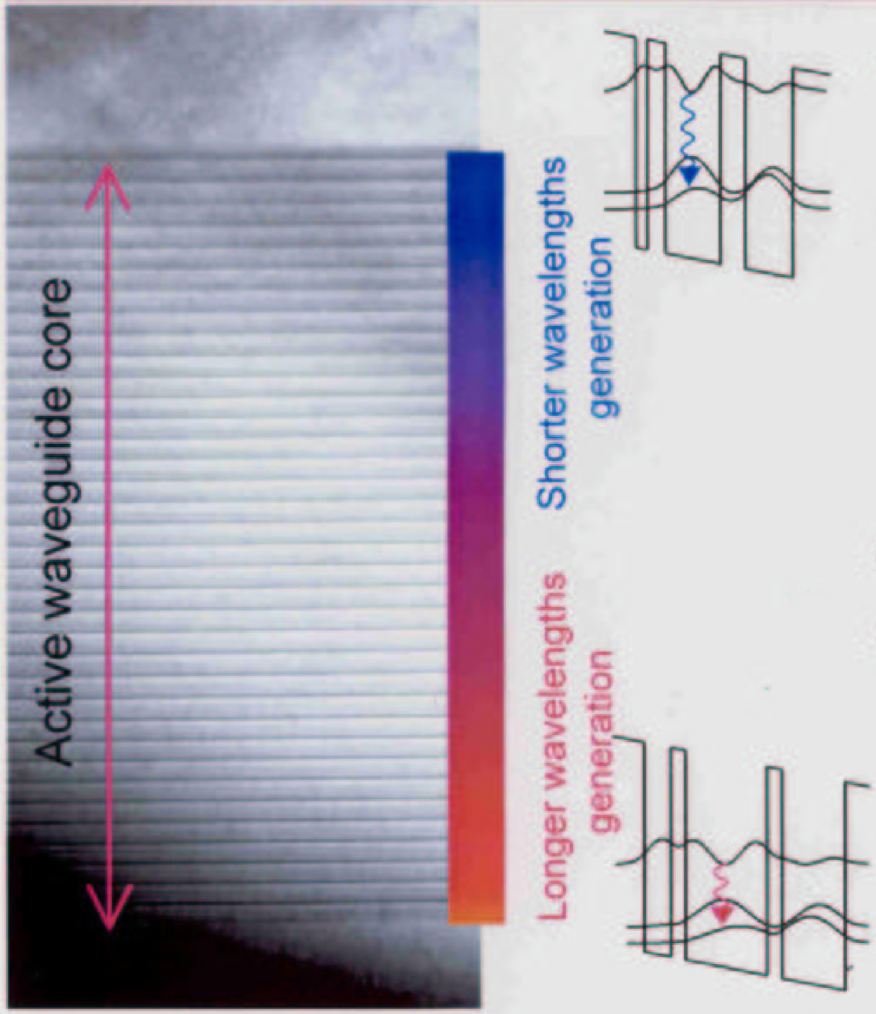


Spectra, laser action at λ ~ 67 μm:

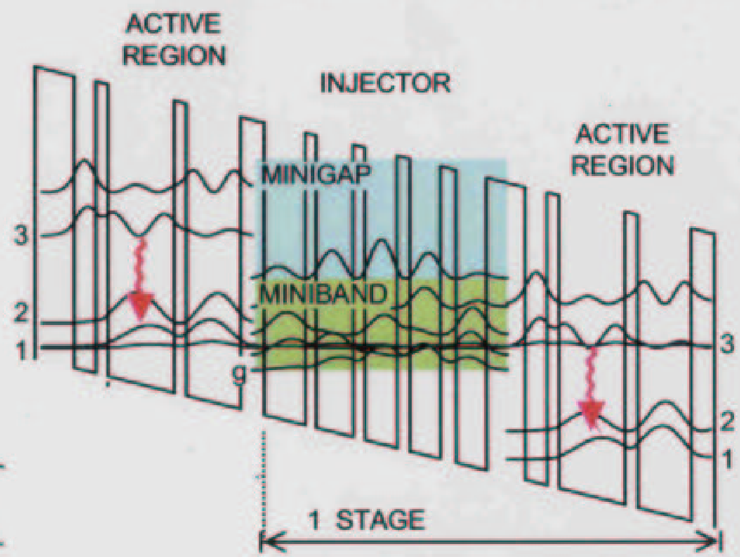


- *first* THz Quantum Cascade laser, designed as GaAs/AlGaAs "chirped superlattice" QC-laser, with very low-loss plasmon-enhanced waveguide

Broadband QC laser: band diagram



- "3-well vertical transition" active regions:
  - simple level structure (designed 30 active regions in two days, then matching injectors)
  - Large dynamic voltage range



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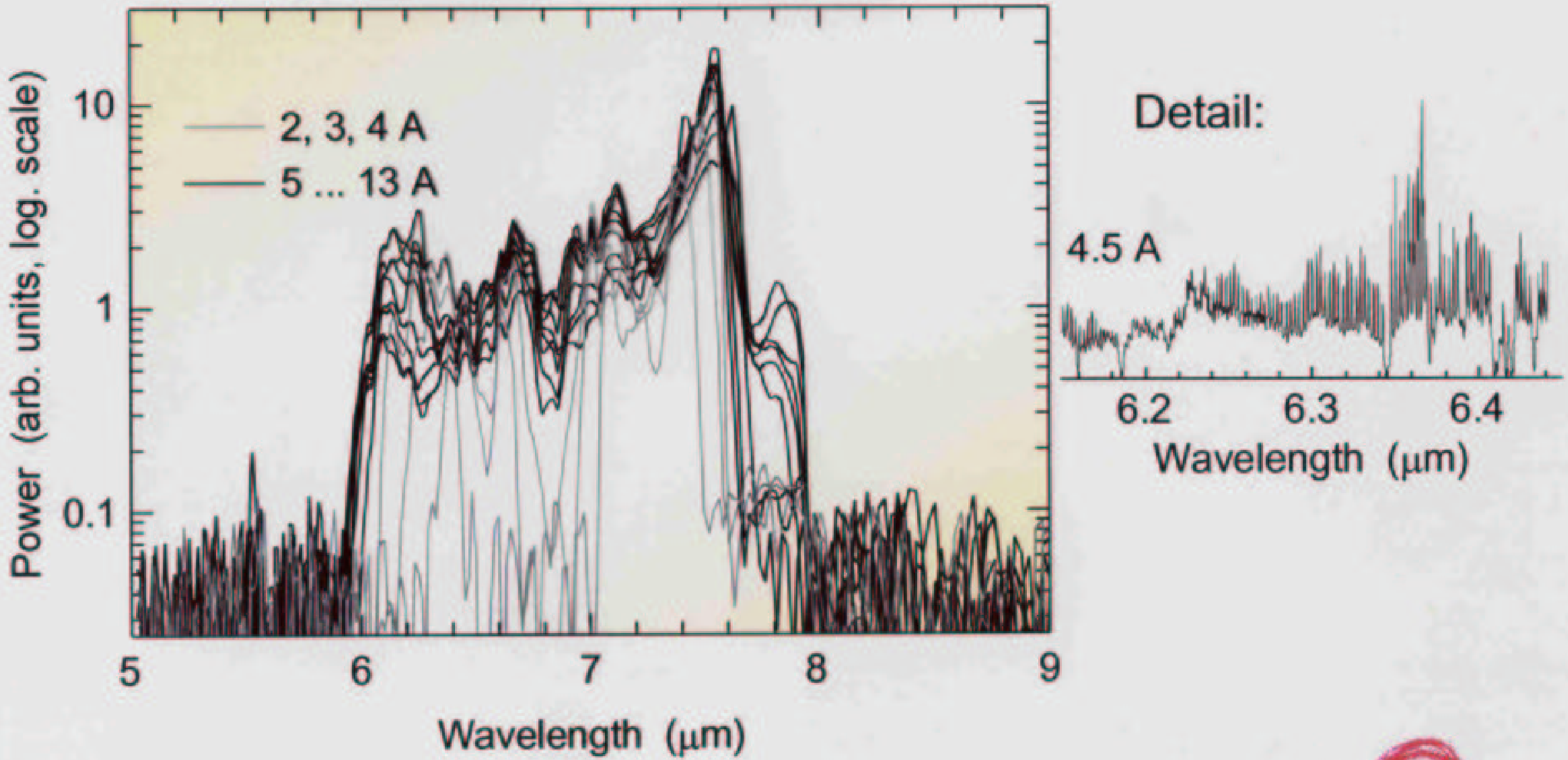
Supercontinuum (6 - 8 μm) spectrum



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Quantum Cascade Laser References

- F. Capasso et al. Physics Today, May 2002
- F. Capasso et al. Physics World, June 1999

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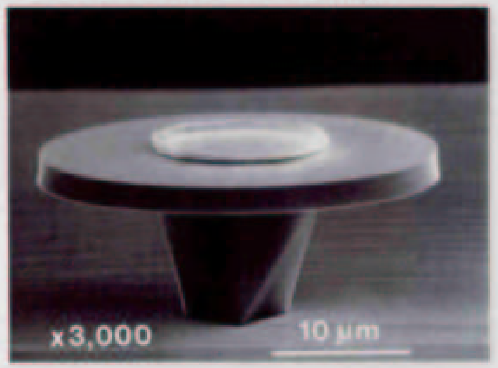
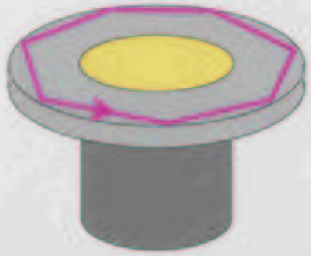
Whispering gallery resonator and QC-lasers

- *whispering gallery resonator:*
  - light trapped through total internal reflection along a closed and convex boundary:

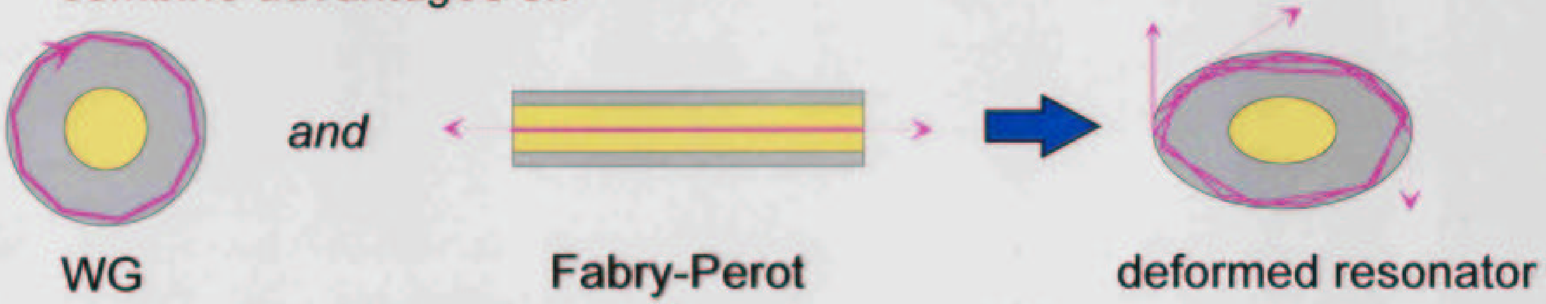




- *whispering gallery and QC-laser: a "perfect" match*
  - unipolar transport: insensitive to surface
  - TM polarization: intrinsically 2-dim system, no vertical losses
  - long wavelength: less sensitive to scattering

Search for high power output and directionality

combine advantages of:



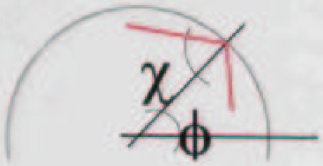
in deformed resonator: *ray impinges on boundary with varying but in average decreasing angle until it escapes by refraction*

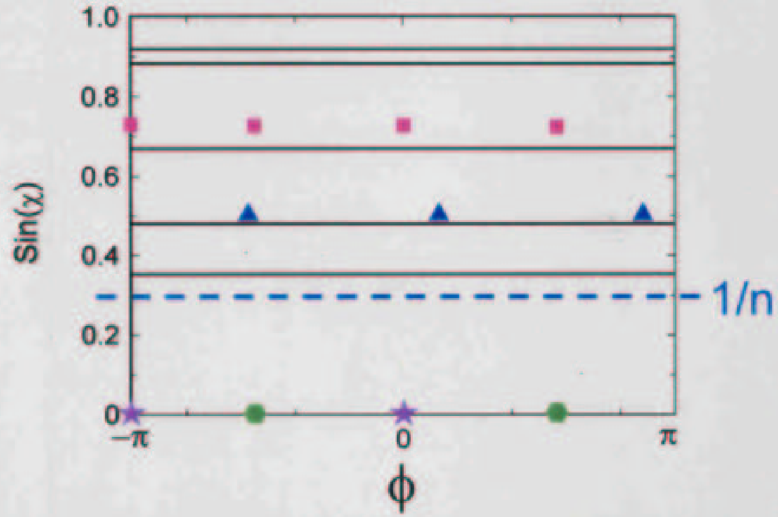
new type of modes "bow-tie" with high reflectivity bounces

- *power:* from refractive escape
- *directionality:* from curvature variation

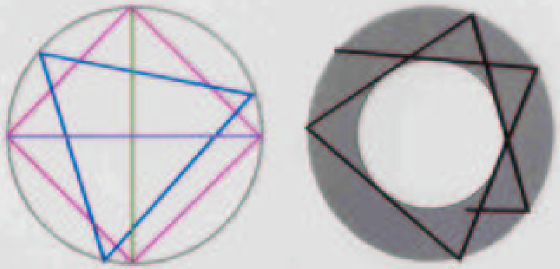
Whispering gallery, ray chaos and orbits

surface of section:

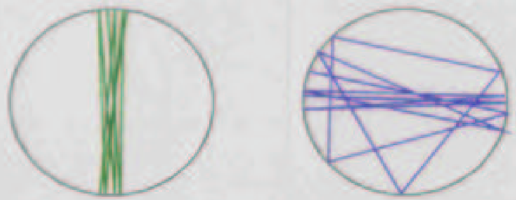




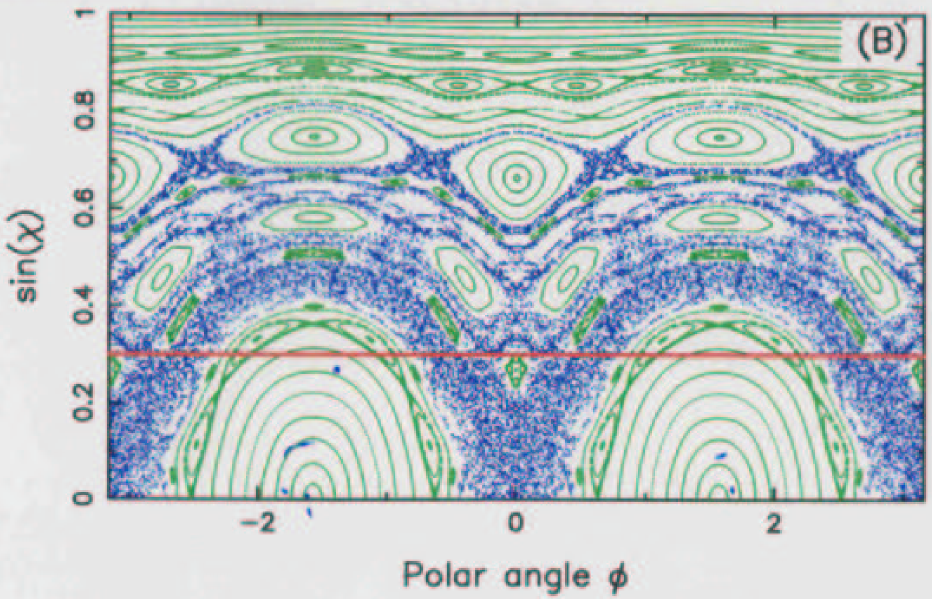
circle:



starting deformation:



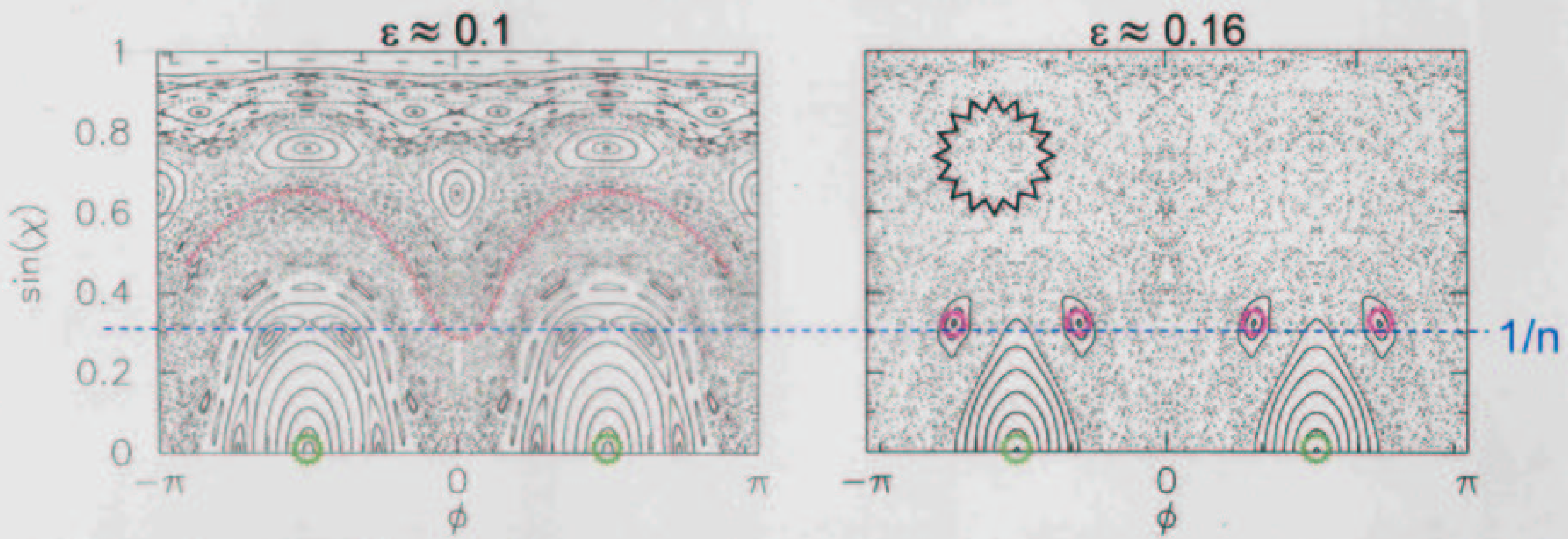
Poincare surface of section ε = *0.06*



- green lines: whispering gallery modes, stable islands
- blue "grainy" regions: chaotic regions

Ray chaos and orbits

A. Douglas Stone, Evgueni E. Narimanov
Yale University, Dep. Appl.Physics, CT



three classes of "modes":

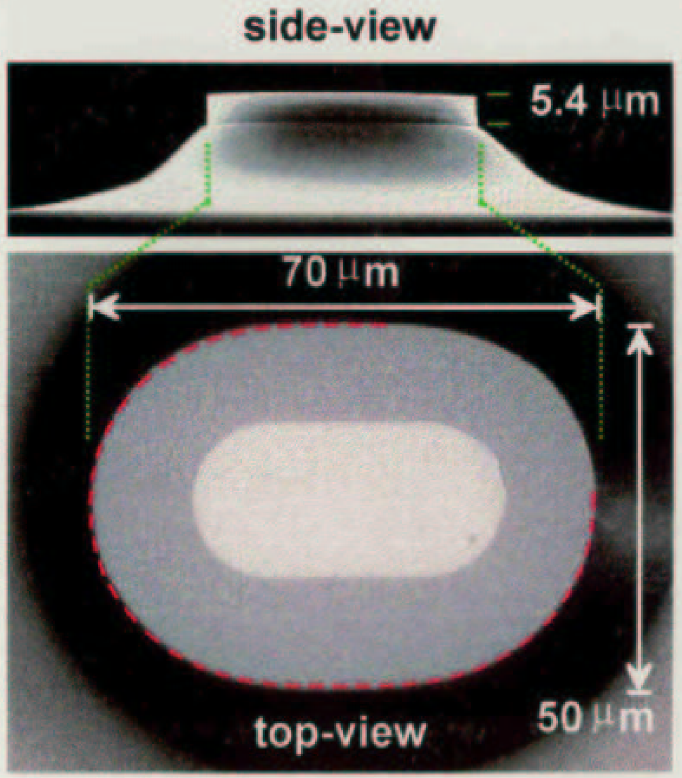
whispering gallery

bouncing ball, bow tie

fully chaotic

deformed cylinder lasers

(picture: $\varepsilon = 0.16$)



flattened quadrupolar deformed cylinder laser:

$r(\phi) \sim \sqrt{(1+2\varepsilon \cos(2\phi))}$

- $\varepsilon = 0$ (circle) - 0.2 (quadrupolar)
- waveguide
  - no coupling to substrate
- 2DEG
  - lateral current spreading
- shape deformation = only source for directionality in the system

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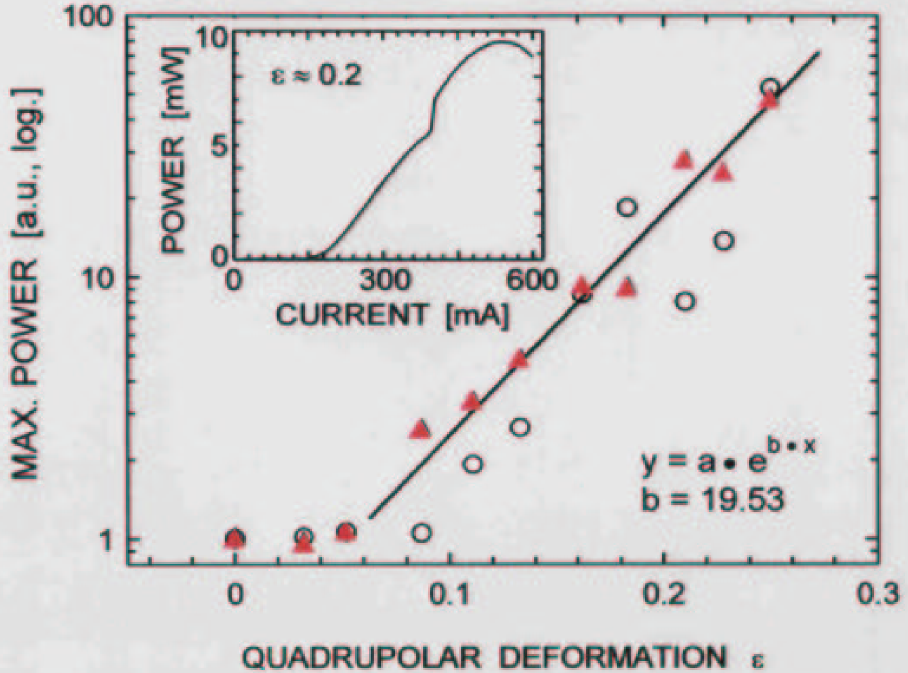
High power output of chaotic WG lasers



- *"exponential"* increase of peak output power *(x 50)*
- collected output power of *~ 10 mW*

- *device characteristic:*
  $\lambda = 5.2\ \mu m$
  pulsed operation
  $T_{max} = 270$ K

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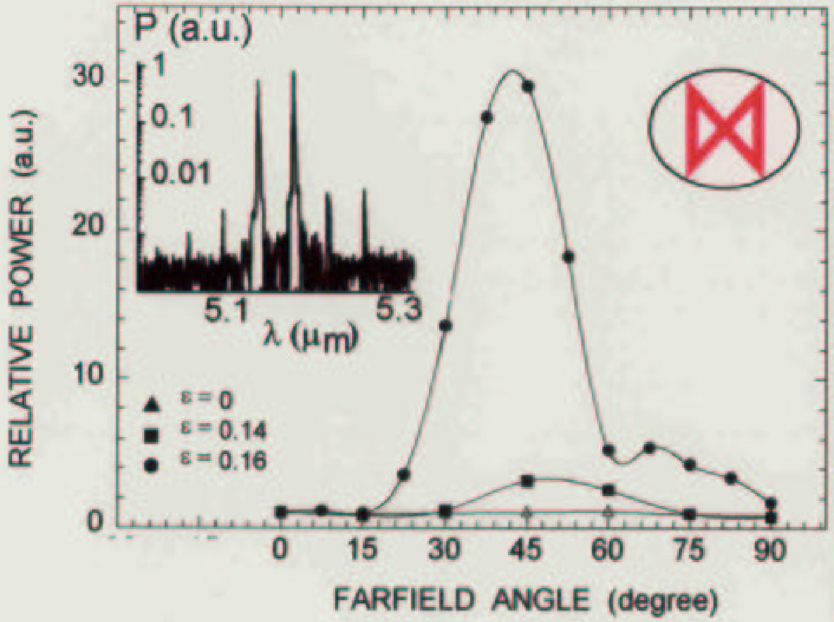
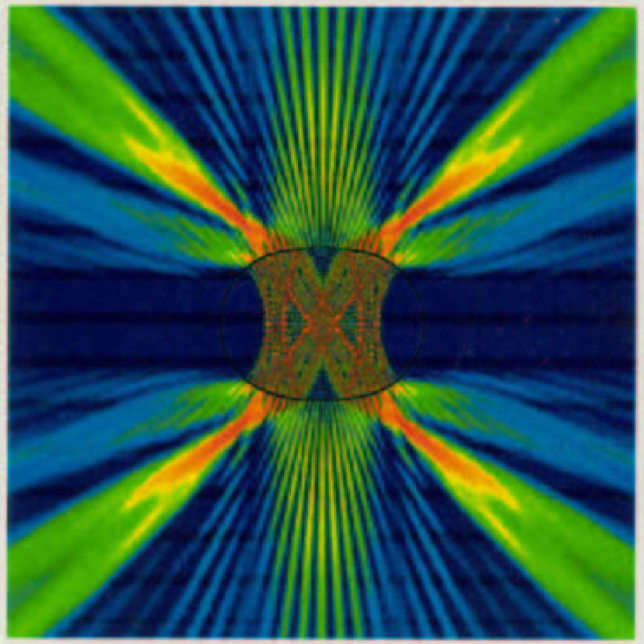
bow-tie modes





Jens U. Noeckel, MPI Dresden, Germany

- *increased power output (per unit angle) in the far-field (x 30)*
- *highly directional emission*

References on Laser Action in Chaotic Optical Billiards

- C. Gmachl et al.
  Science vol. 280, 1556 (1998)
- C. Gmachl et al.
  Optics Letters, vol. 27, 824 (2002

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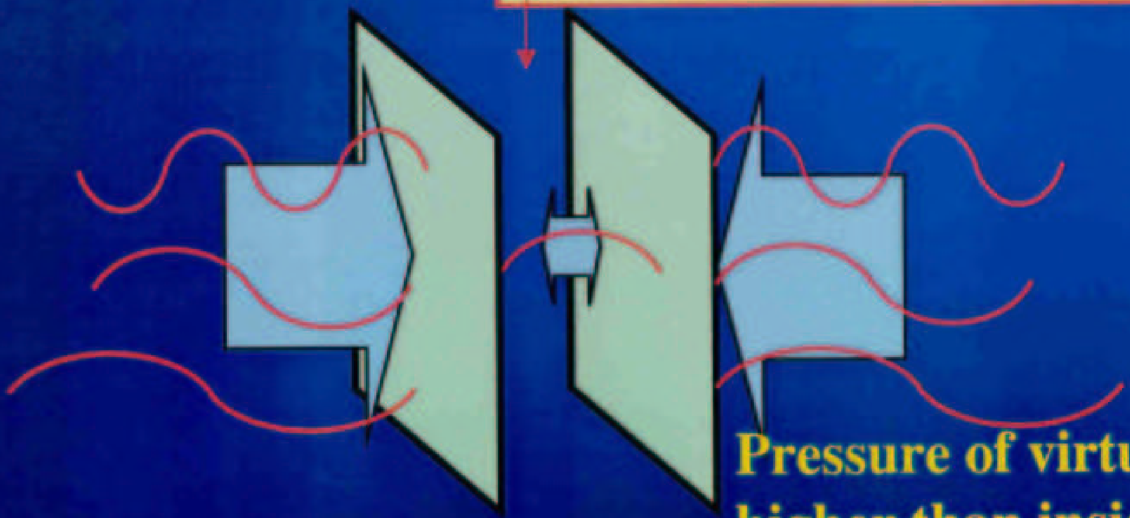
Casimir Force

Vacuum is not empty in quantum mechanics: it teems with virtual particles (photons, etc) appearing and disappearing (Vacuum Energy).

Fluctuating electromagnetic fields associated with virtual photons cause an attraction between metallic plates: Casimir effect (1948)

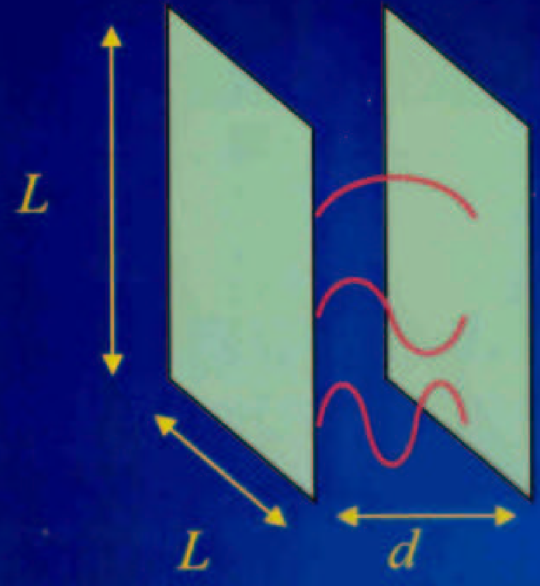
Only short wavelengths can fit inside the metal plates



Pressure of virtual photons outside is higher than inside ⇒ ATTRACTION

1 atmopshere at 100 nanometers !!

Derivation of Casimir force



$$\omega_{k_x k_y n} = c\left(k_x^{\,2} + k_y^{\,2} + \frac{\pi^2}{d^2} n^2\right)^{1/2}$$

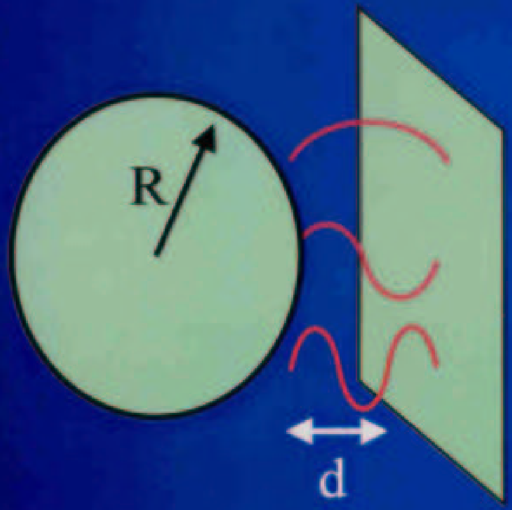
Total zero point energy: $E = \sum_{k_x k_y n} \frac{1}{2}\hbar\omega_{k_x k_y n}$

$$E(d) = \frac{\hbar c L^2}{\pi} \sum_n \int_0^\infty \mathrm{d}k_x \int_0^\infty \mathrm{d}k_y \left(k_x^{\,2} + k_y^{\,2} + \frac{\pi^2}{d^2} n^2\right)^{1/2}$$

Potential energy of the plates: $U(d) = E(d) - E(\infty) = -\frac{\pi^2 \hbar c}{720 d^3} L^2$

Casimir force $F = {-U'(d)}/{L^2} = -\frac{\pi^2 \hbar c}{240 d^4}$

Experiments measuring Casimir force:



$$F_{Casimir} = -\frac{\pi^3 R}{360}\frac{\hbar c}{d^3}$$

- Sparnaay '1958

  100 % uncertainty

- Lamoreaux '1997

  Torsional Pendulum

  5% agreement with theory

- Mohideen & Roy '1998

  AFM

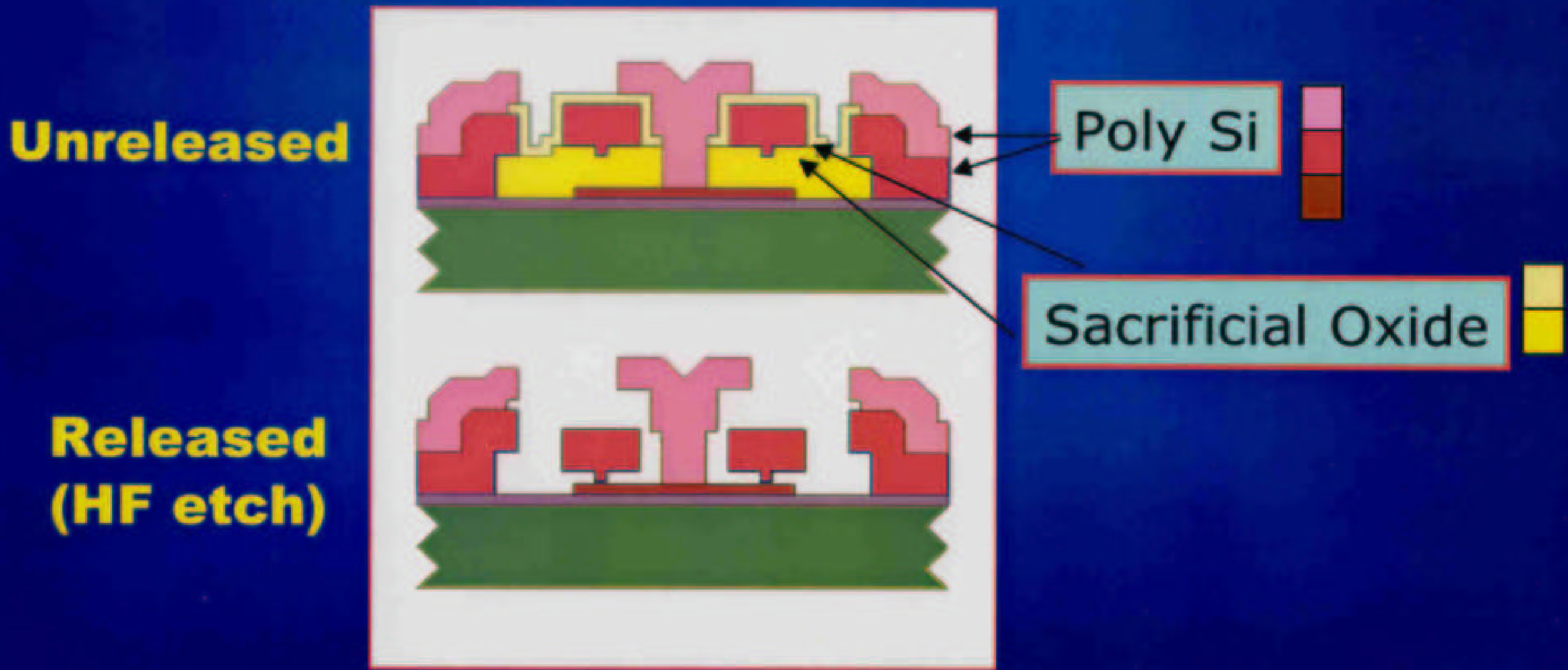
  1 % agreement with theory

Surface Micromachining

Fabrication on top of substrate:

Structural layers: polycrystalline-Silicon

Sacrificial layers: Silicon Oxide

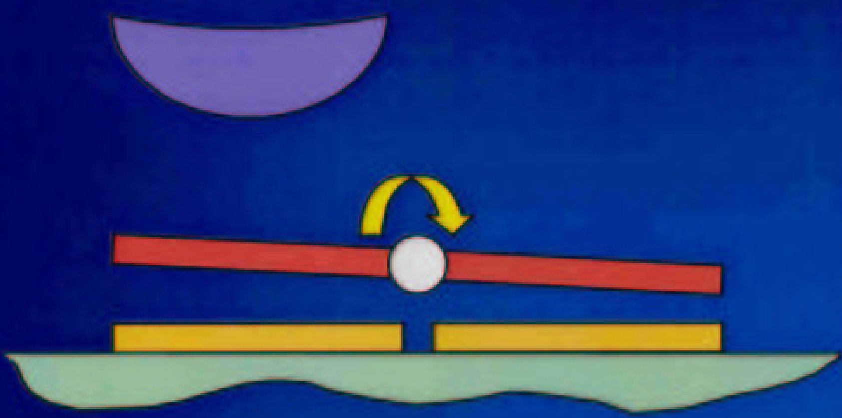


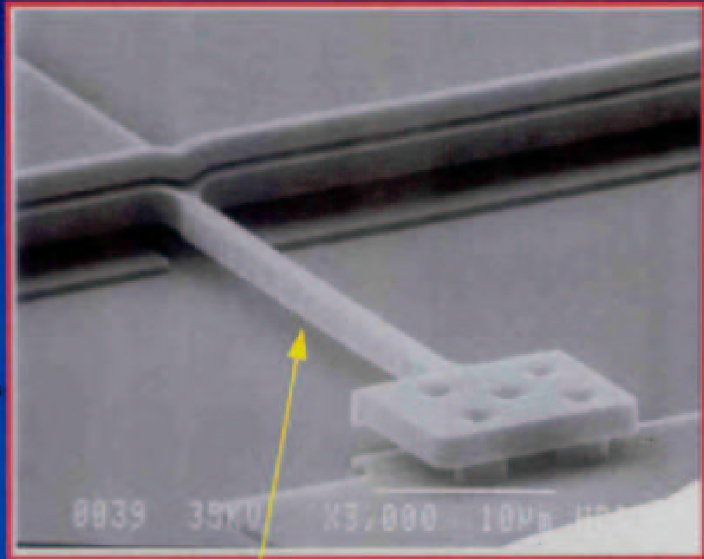
Motivations:
demonstrate quantum effects in MEMS

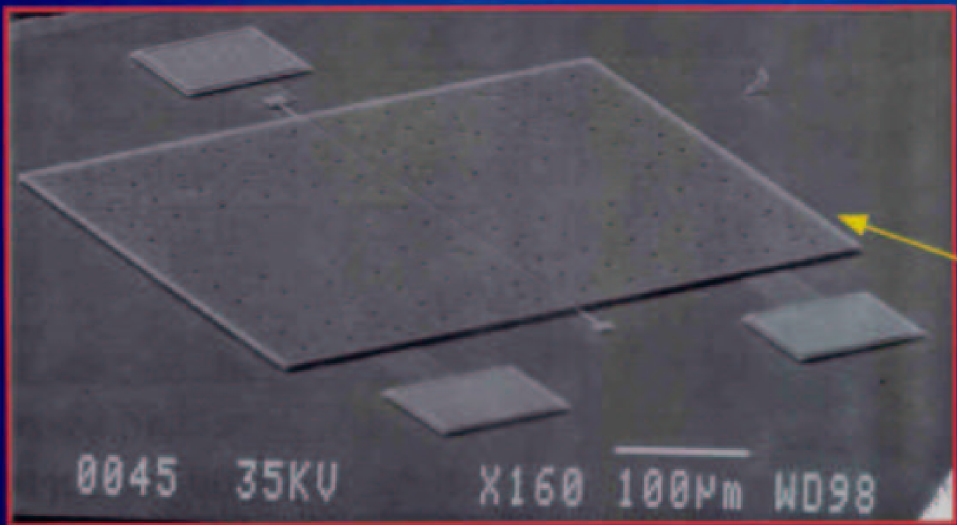
- Make use of the high sensitivity of MEMS sensors to do a precision measurement of Casimir force

- With further miniaturization, Casimir force may play a role in the operation of MEMS

MEMS torque device



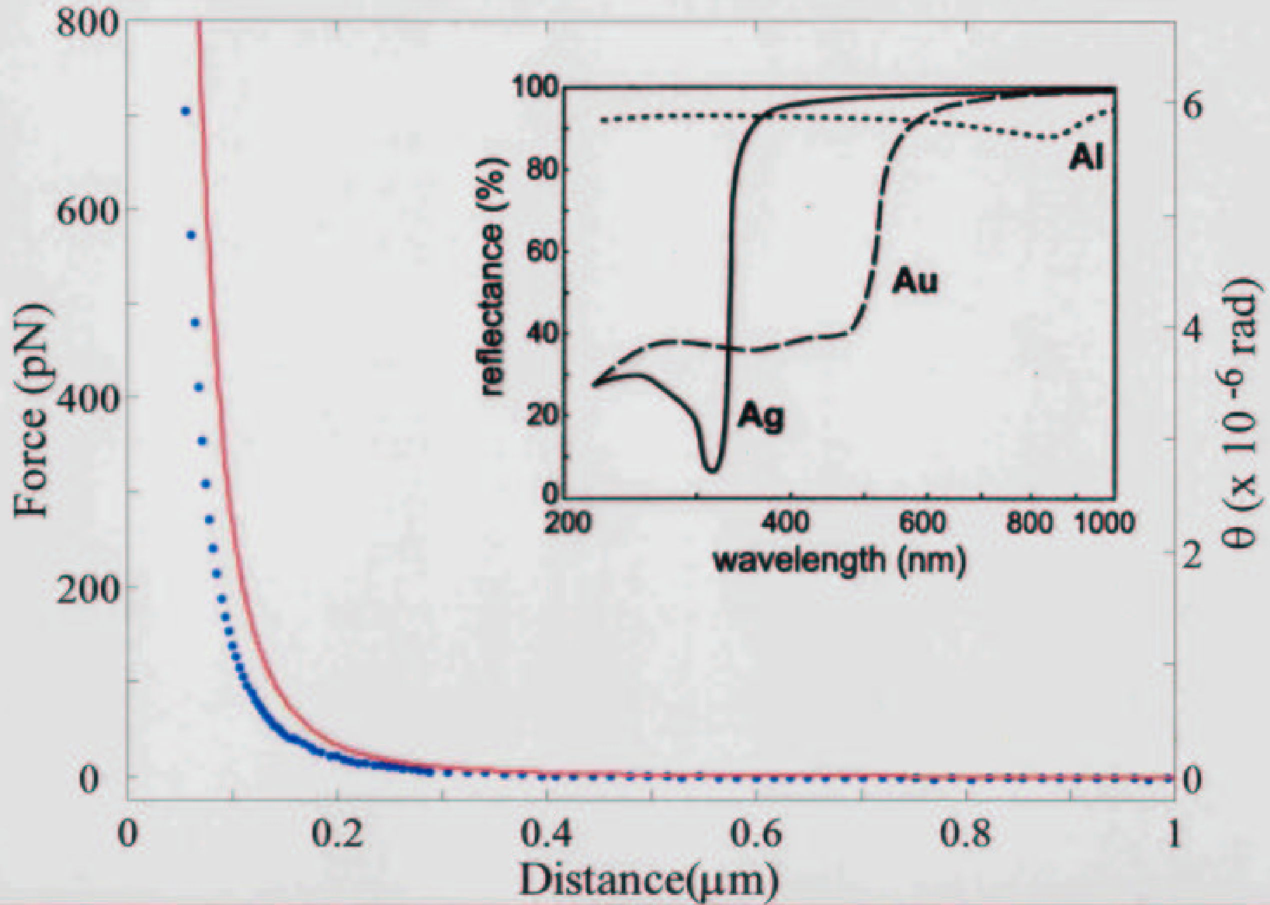




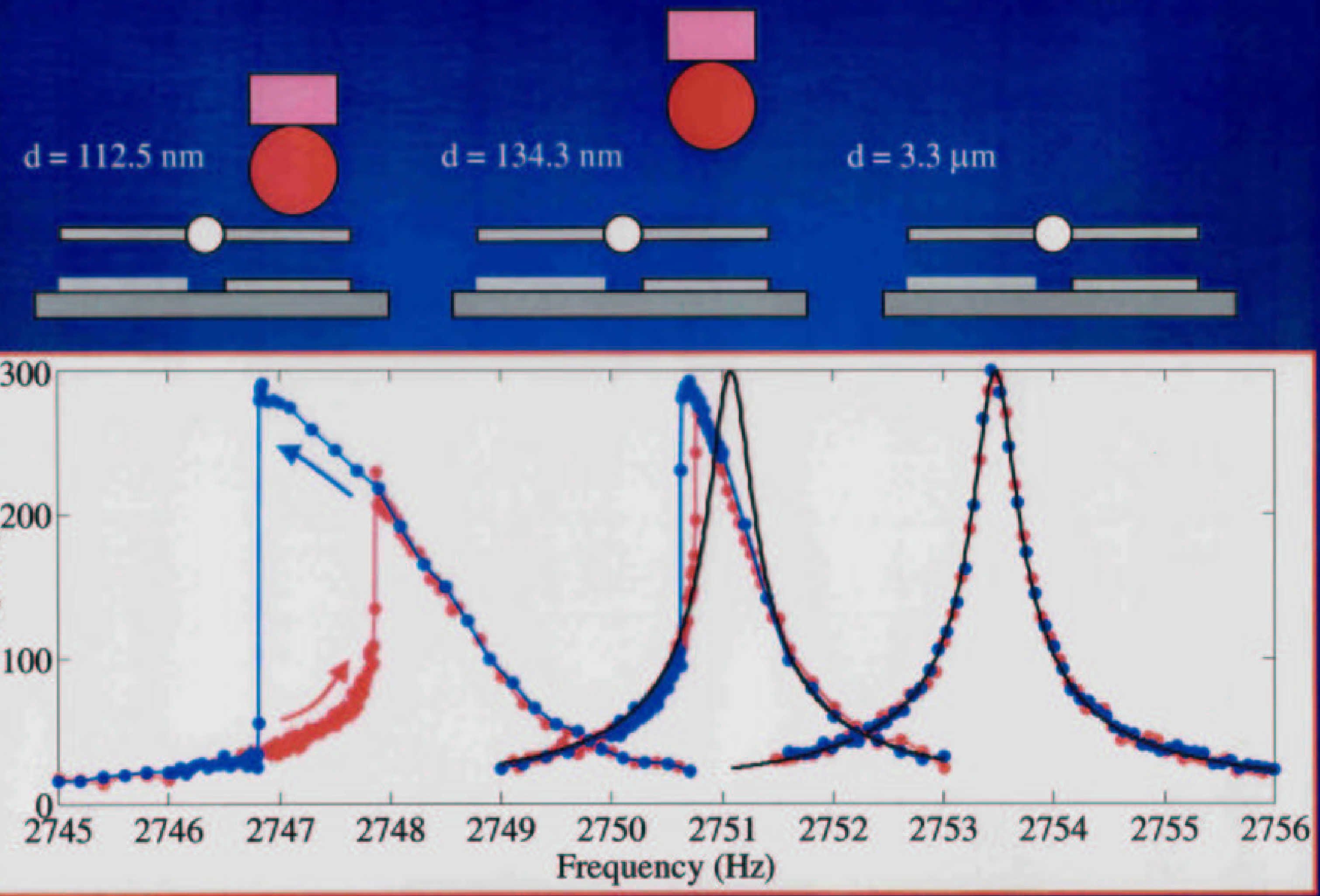
Torsional rod
cross section: 1.5 x 2 μm^2

poly-Si plate:
500 µm x 500 µm x 3.5 µm

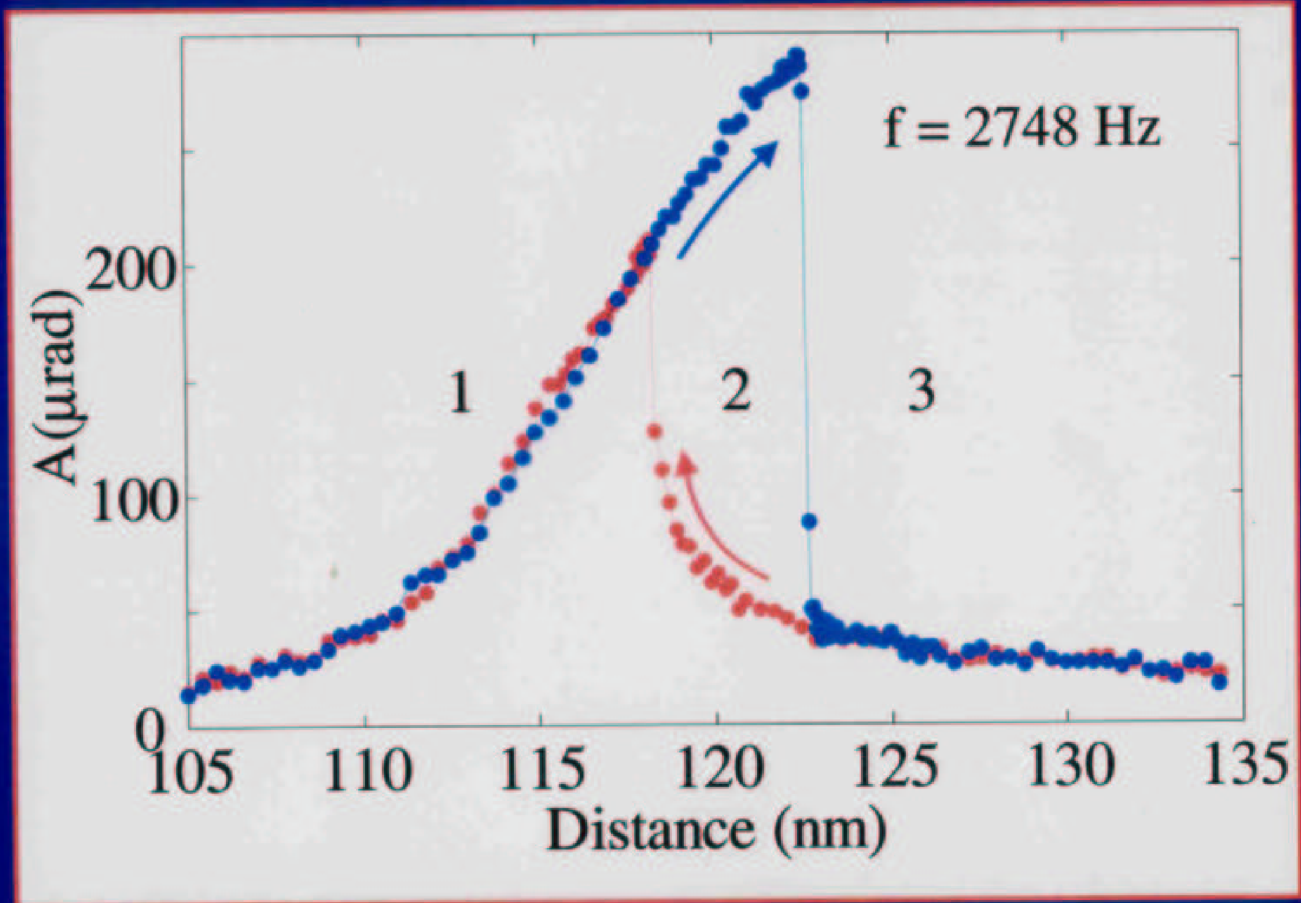
Gold surface is an imperfect reflector at UV



Nonlinear behavior induced by the Casimir force



Position sensor based on the Casimir force



Oscillation amplitude depends on whether oscillator is in region 1 or region 3 before it enters region 2

Nanomechanics Based on Casimir Forces

- H. B. Chan, V. Aksyuk, R. N. Kleiman, D. J. Bishop F. Capasso, Science, vol. 291, 1941 (2001)
- H. B. Chan, V. Aksyuk, R. N. Kleiman, D. J. Bishop F. Capasso, Phys. Rev. Lett. 87, 211801 (2001)

Future directions

- Changes in Q: dissipative Casimir force (Casimir friction).
- other geometries: predicted repulsive Casimir force in a spherical conducting shell and in a "pizza box"
- dynamic Casimir effect: creation of pairs of photons by a vibrating capacitor