"Polaritonic crystals: from optical response to Casimir effect "

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Polaritonics: From Basic Research to Device Applications
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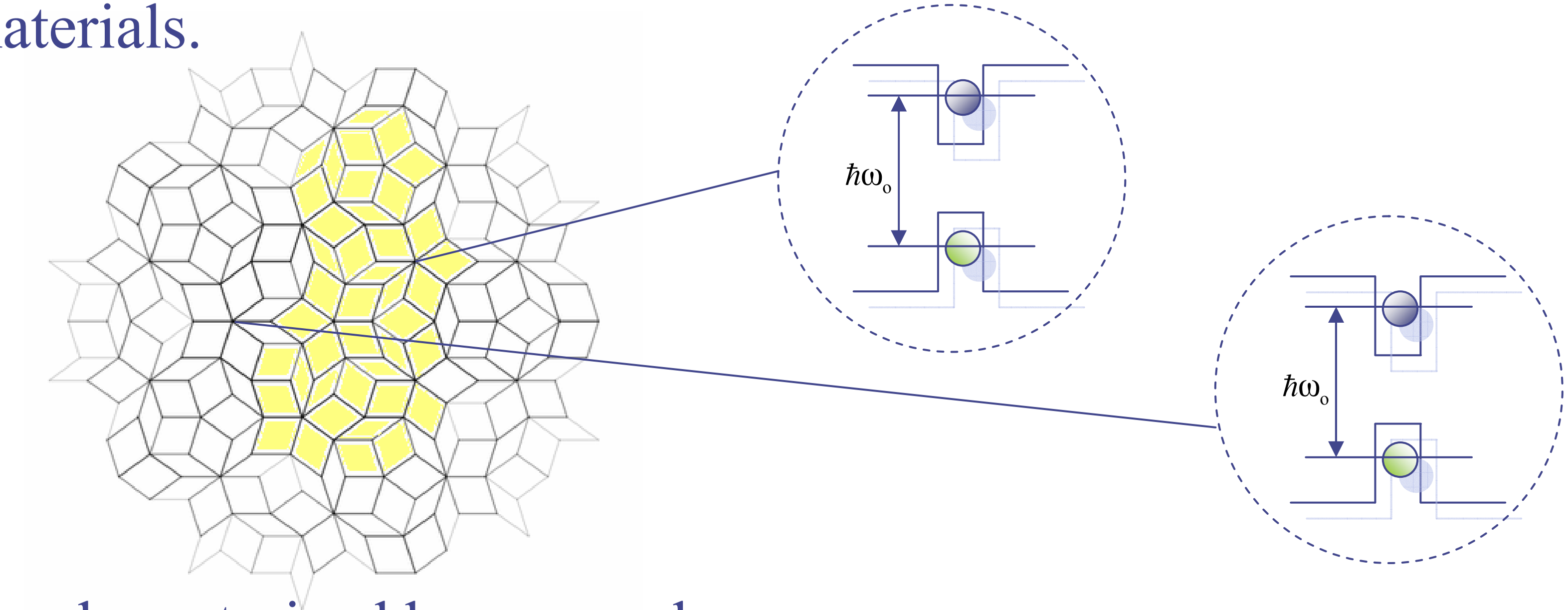
Outline

- **Introduction**
  - Polaritonic Crystals
    - periodic structures: superradiance, polaritonic crystal limit
    - quasicrystals: scaling and fractality
- **Optical response**
  - e.m. Green function for a general shaped superstructure
- **Casimir effect**
  - definition
  - material design for force control
    - numerical approach
    - preliminary results

Polaritonic crystals

Polaritonic crystals are structured media (photonic crystals) with polariton poles in the dielectric susceptibility of some constituent materials.



Are characterized by a complex dielectric tensor, function of spatial variables and frequency.

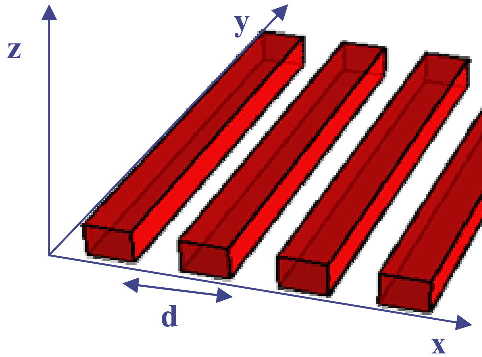
$$\varepsilon_{ij}(\vec{r},\omega) = \varepsilon_{ij}^{'}(\vec{r},\omega) + i\varepsilon_{ij}^{''}(\vec{r},\omega)$$

In the photonic crystal limit

$$\varepsilon(\vec{r},\omega) = \varepsilon'(\vec{r})$$

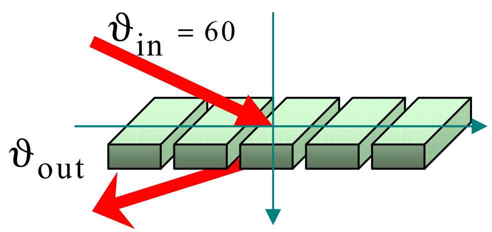
Subwavelength nanostructured surfaces

Self-sustained dielectric grating slab can show

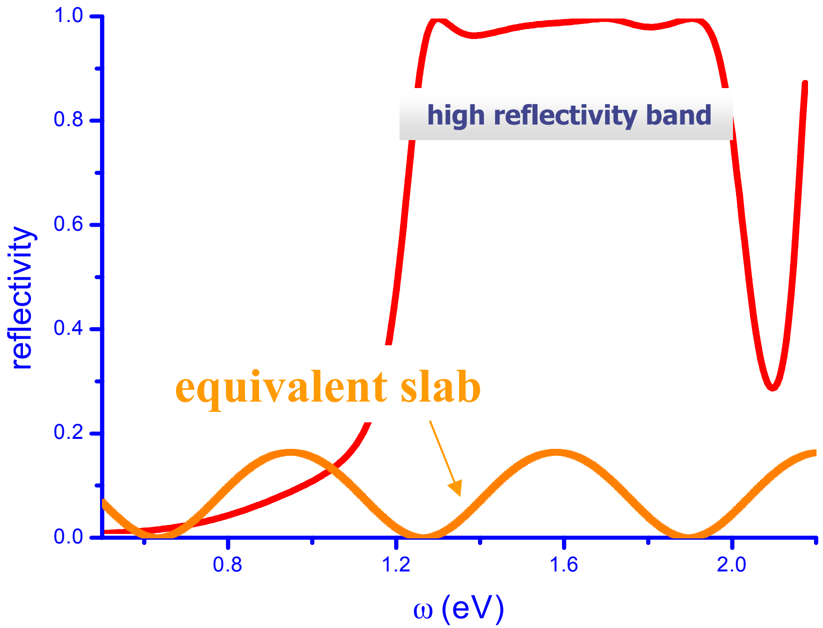


giant reflection bands

negative transmission



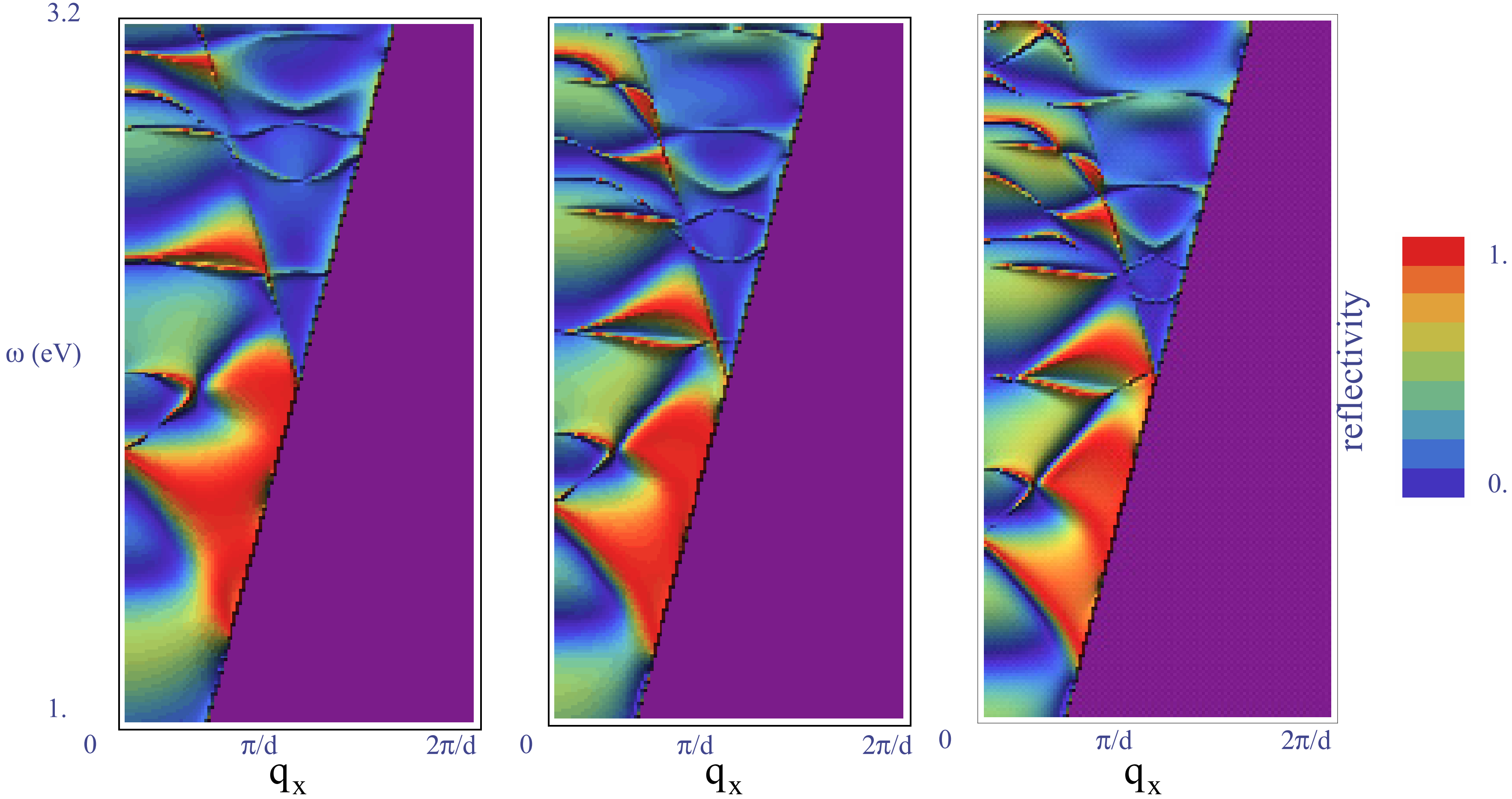
R >95%



Mirror effect at the Brewster angle in semiconductor rectangular gratings
L.Pilozzi, A. D'Andrea, H. Fenniche, Phys.Rev. B **64**, 235319 (2001)

Subwavelength nanostructured surfaces

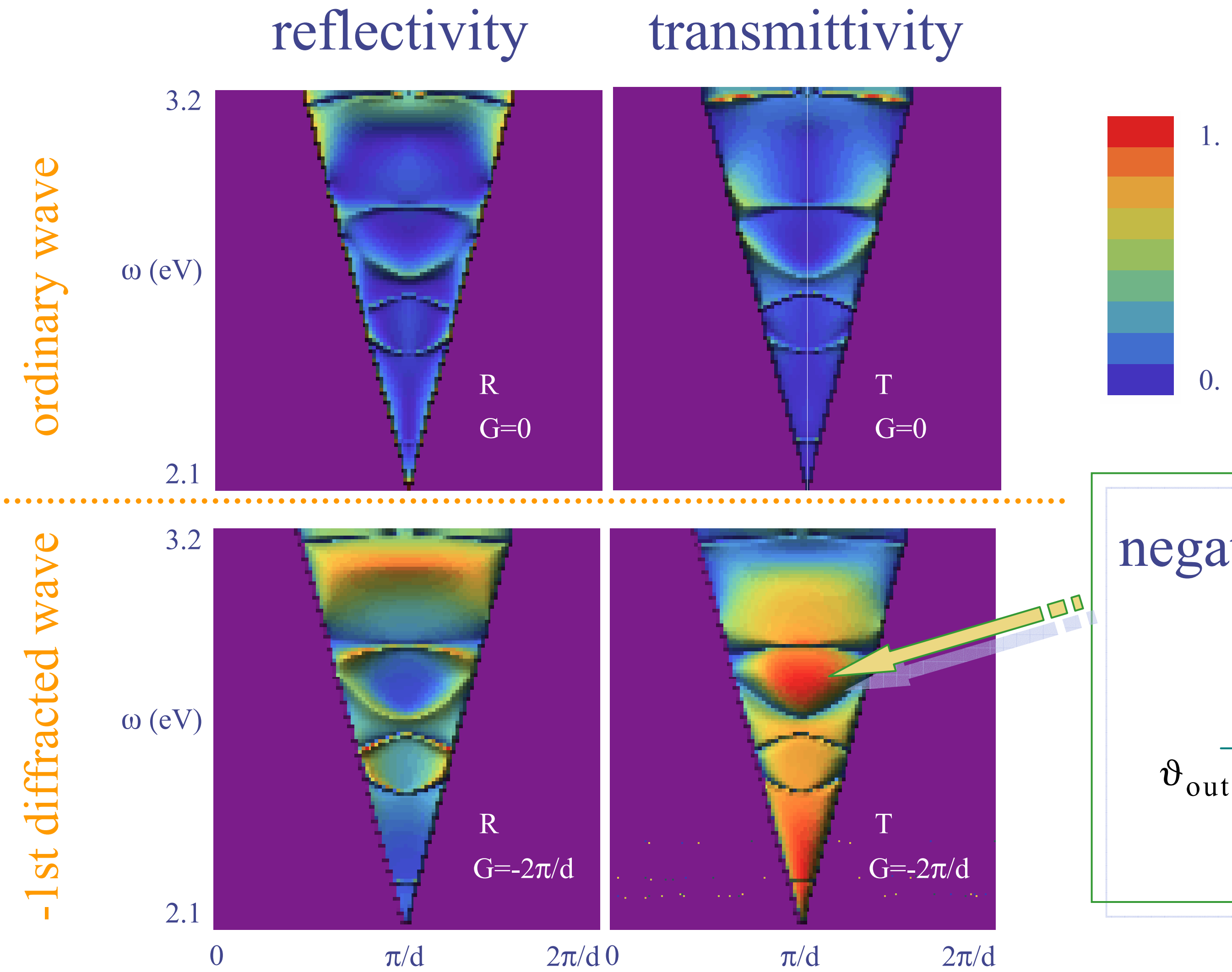
Reflectivity maps

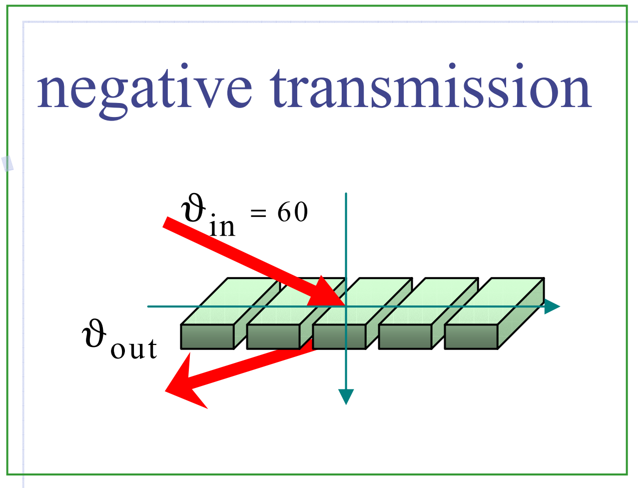


$f_x = 2/3$ $f_x = 3/4$ $f_x = 4/5$

f_x = filling factor

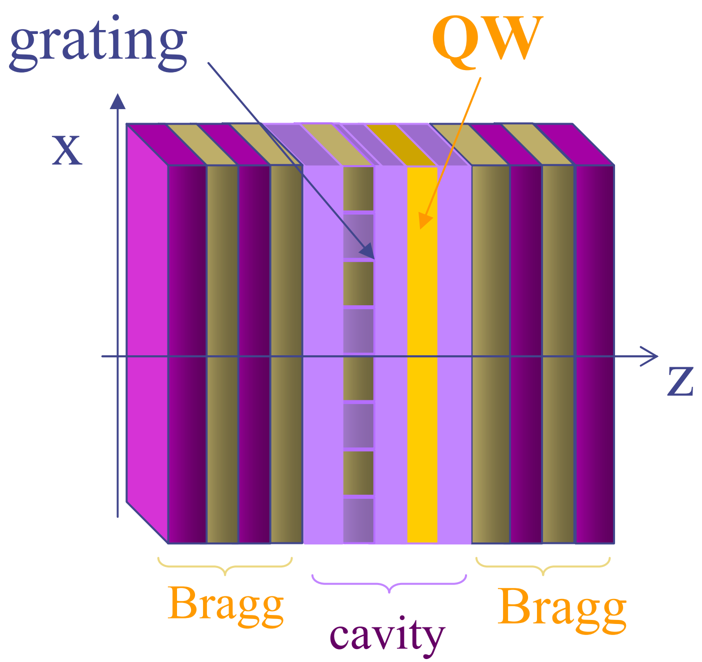
Subwavelength nanostructured surfaces

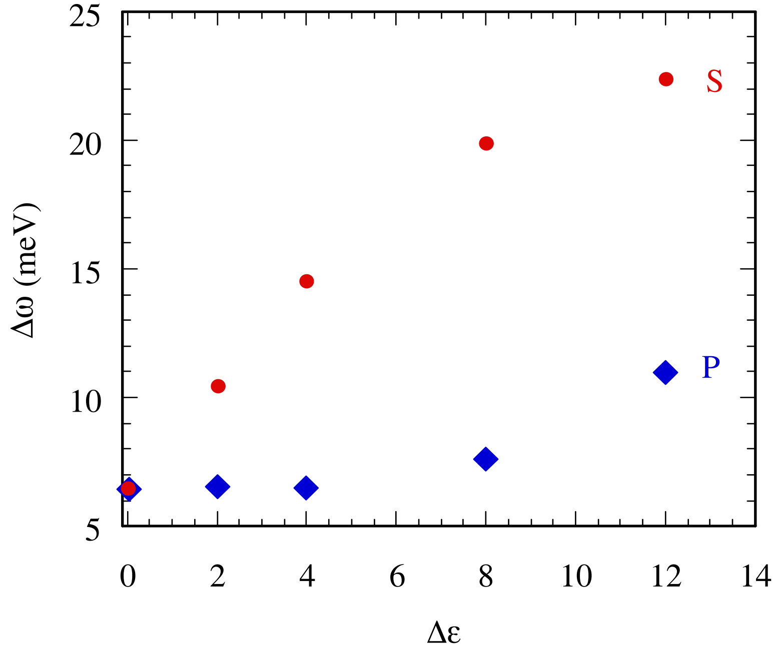




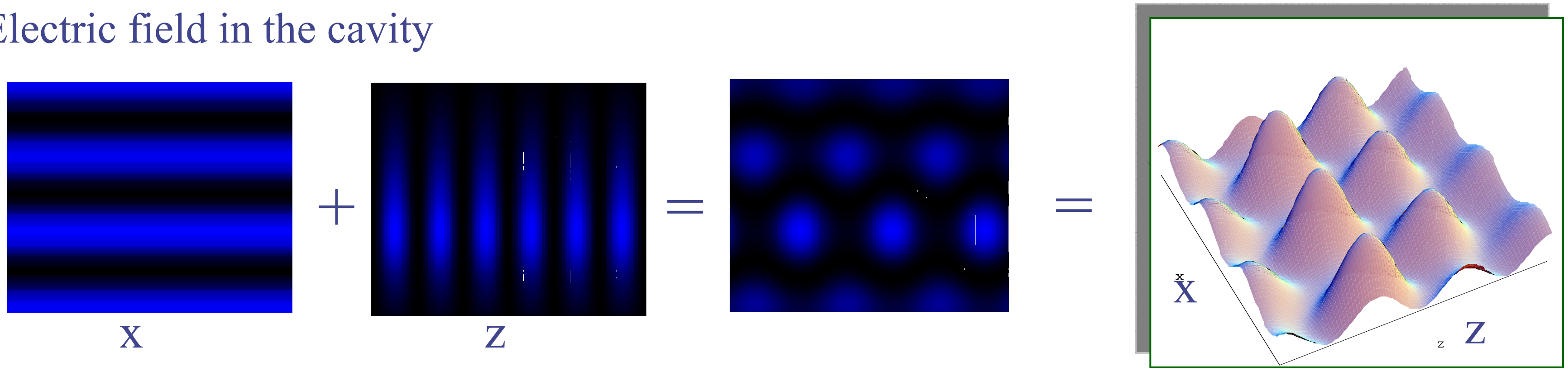
Patterned cavities

Rabi splitting enhancement





Electric field in the cavity



Grating-induced enhancement of exciton-polariton Rabi splitting in a planar microcavity

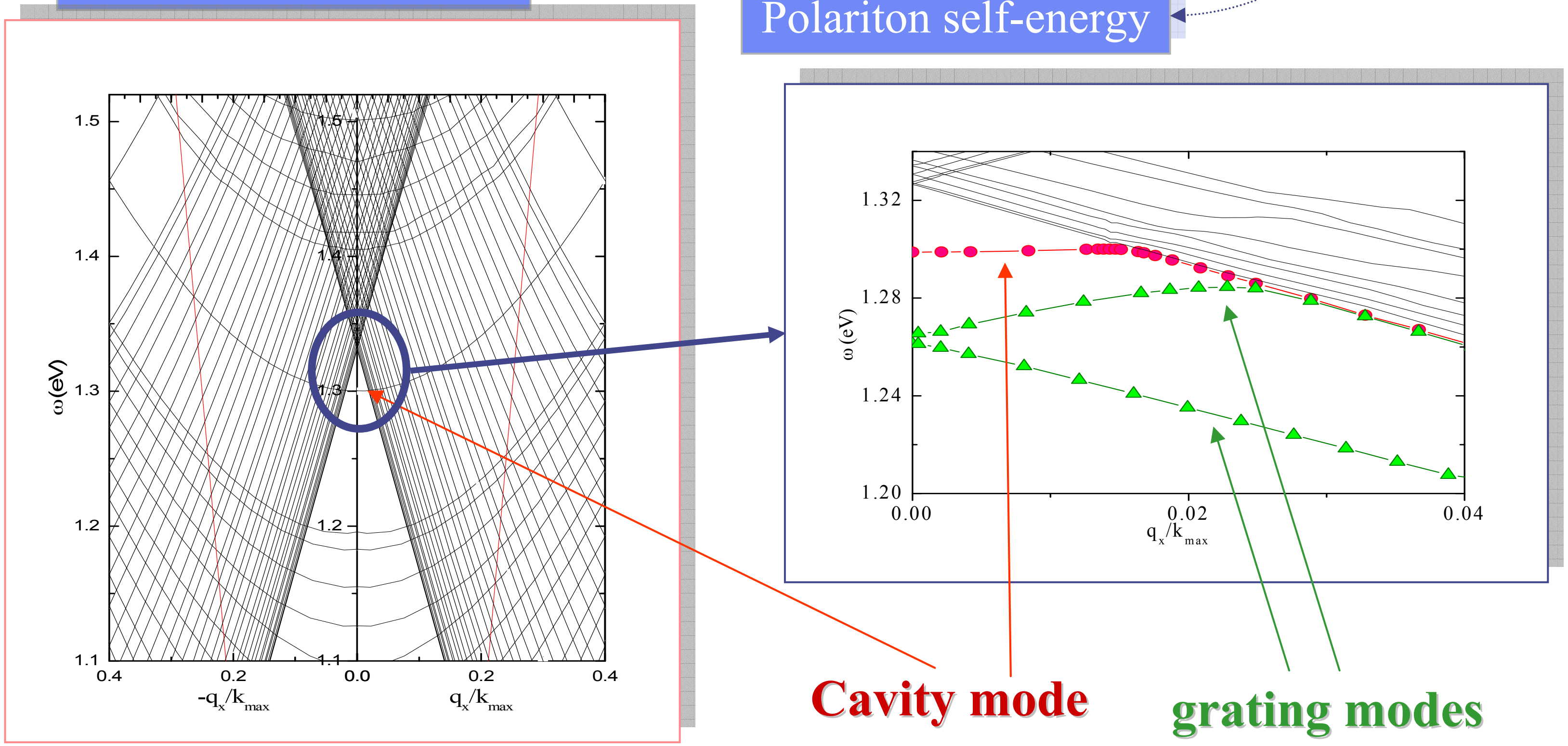
L.Pilozzi, A. D'Andrea, Phys.Rev. B **61**, 4771 (2000)

Patterned cavities

$$G_{cp}(z,z',\omega,k_{//}) = g(z,z',\omega,k_{//}) + \frac{h_{ox}(z,\omega)\,h_{xo}(z',\omega)}{E_x(k_{//}) + \Sigma_{xx}(k_{//},\omega) - \hbar\omega - i\gamma}$$

Cavity polariton modes

Polariton self-energy



Effect of lateral periodicity on the optical response of a quantum well in a distributed Bragg reflector cavity: A simplified description via the Green function of a cavity polariton
L.Pilozzi, A. D'Andrea, k. Cho, Phys.Rev. B **76**, 245312 (2007)

Polaritonic crystals

Microscopic nonlocal response theory

$$\varepsilon(\vec{r},\vec{r}\,',\omega) = \varepsilon_b(\vec{r},\omega) + 4\pi\chi(\vec{r},\vec{r}\,',\omega)$$

- Microscopic self-consistent approach

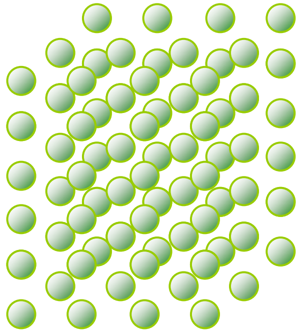
- Characteristic optical features dependent on system size and shape.

the microscopic spatial structure of the polarization → reflects on → the response field intensity

$$\vec{P}\,'(\vec{r},\omega) = \int d^3r'\,\chi'(\vec{r},\vec{r}\,',\omega)\,\vec{E}(\vec{r}\,',\omega)$$

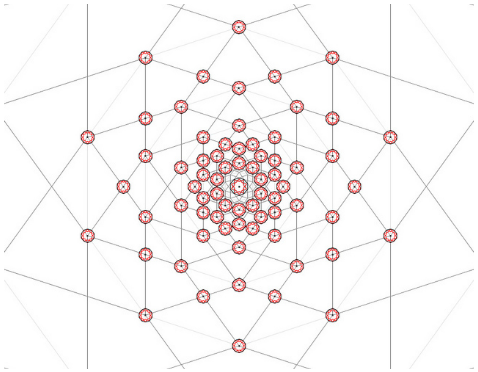
Polaritonic crystals

crystals



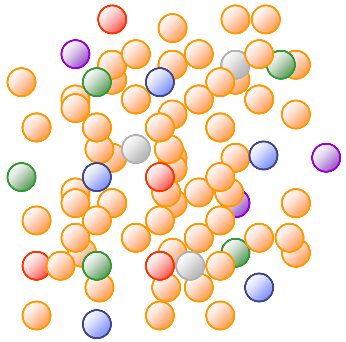
long range order
and
periodicity

quasicrystals



long range order
no periodicity

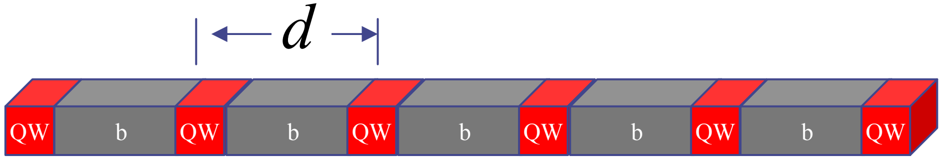
disordered systems



no long range order
no periodicity

Periodic structures

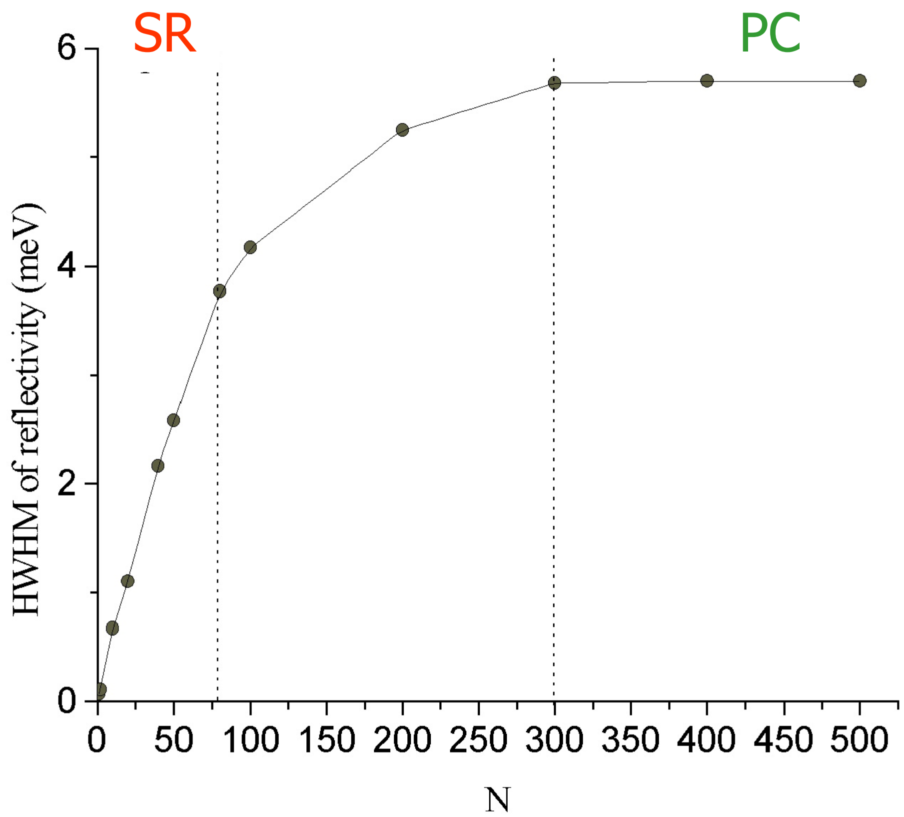
MQW: superradiance (SR) and polaritonic crystal (PC) limit



$$d = \frac{\lambda(\omega_o, \varepsilon_b)}{2}$$

ω_o = exciton resonance

N=quantum well number

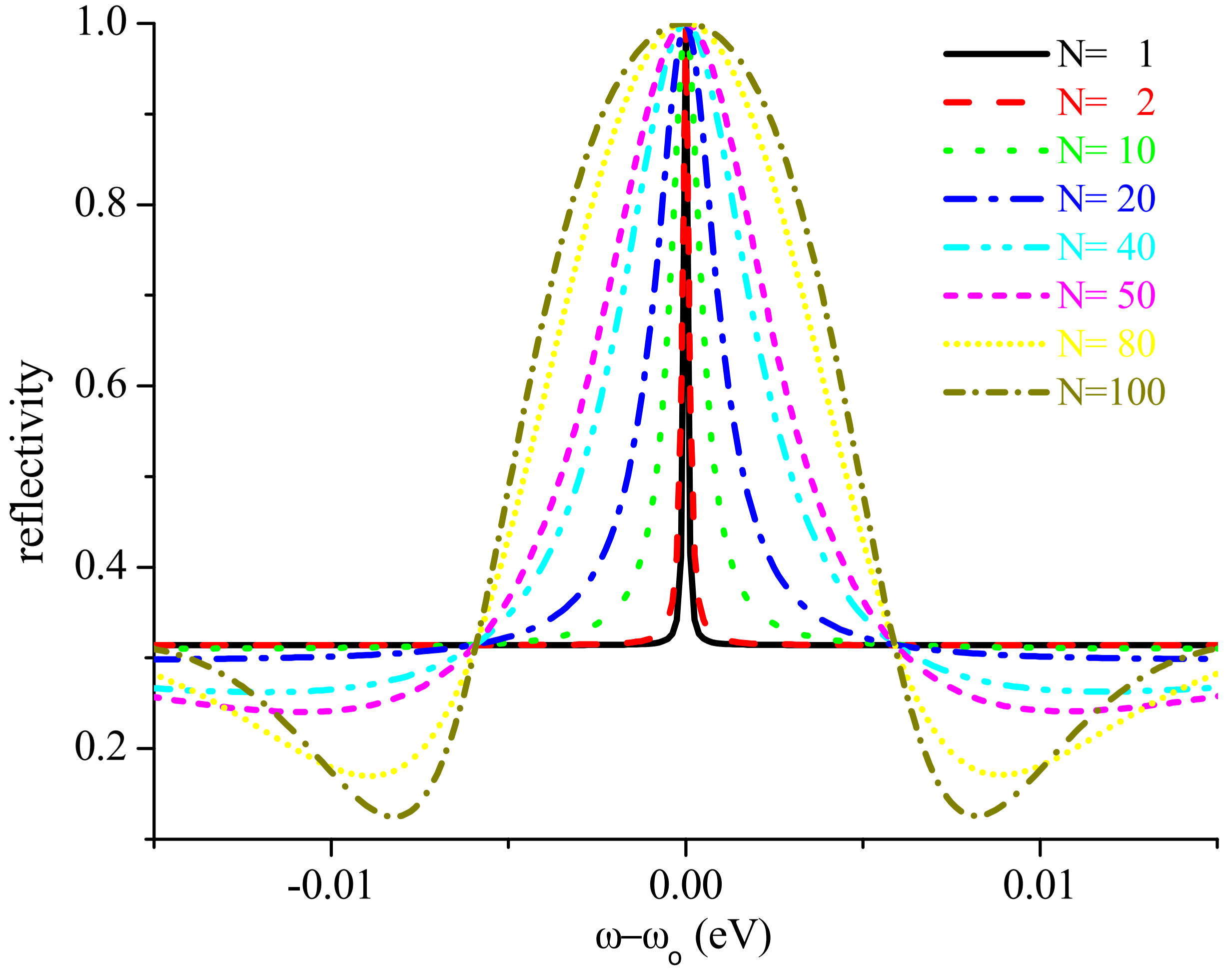


Spatial dispersion effects on the optical properties of a resonant Bragg reflector

L.Pilozzi, A. D'Andrea, K. Cho, Phys.Rev. B **69**, 205311 (2004)

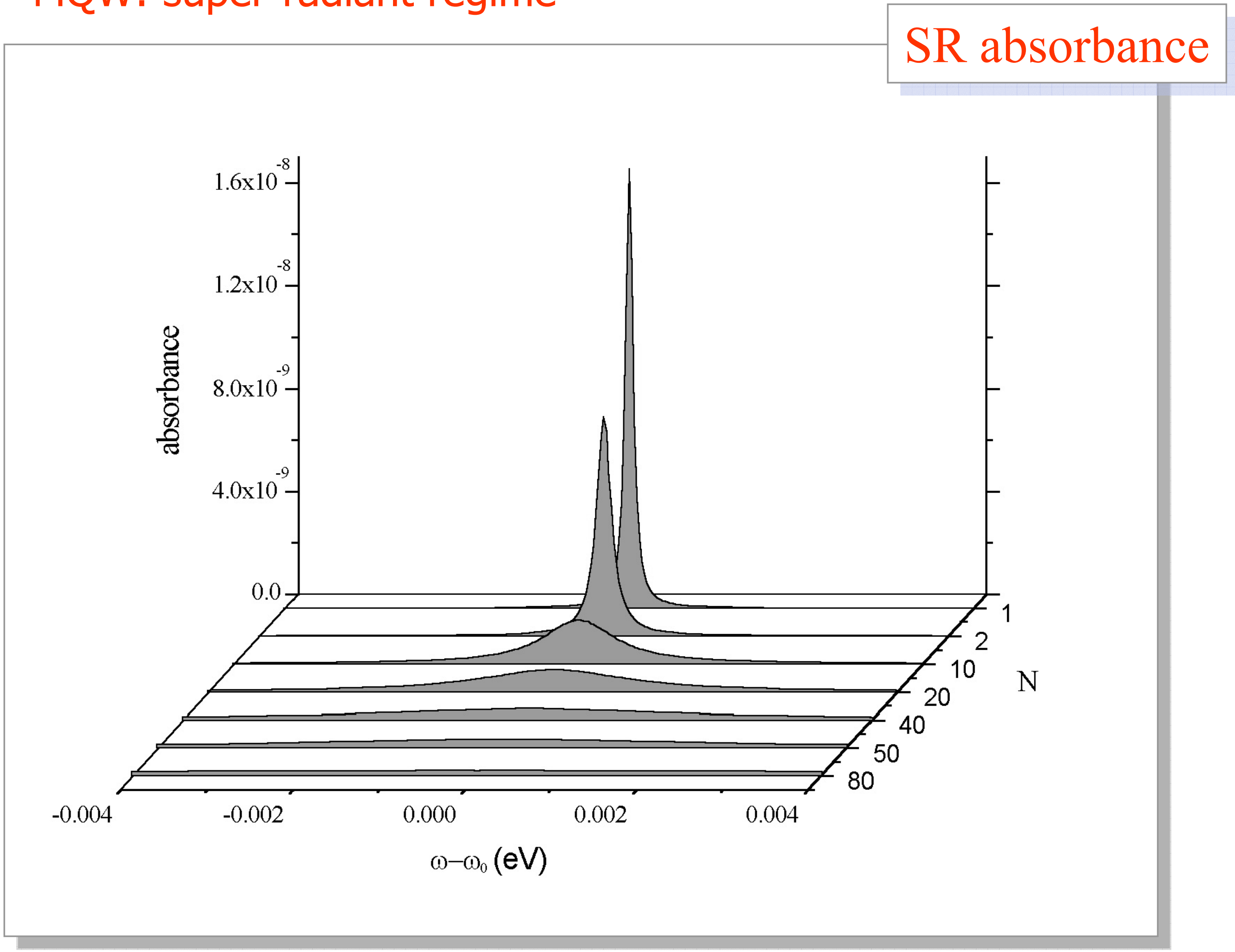
MQW: super-radiant regime

SR reflectivity



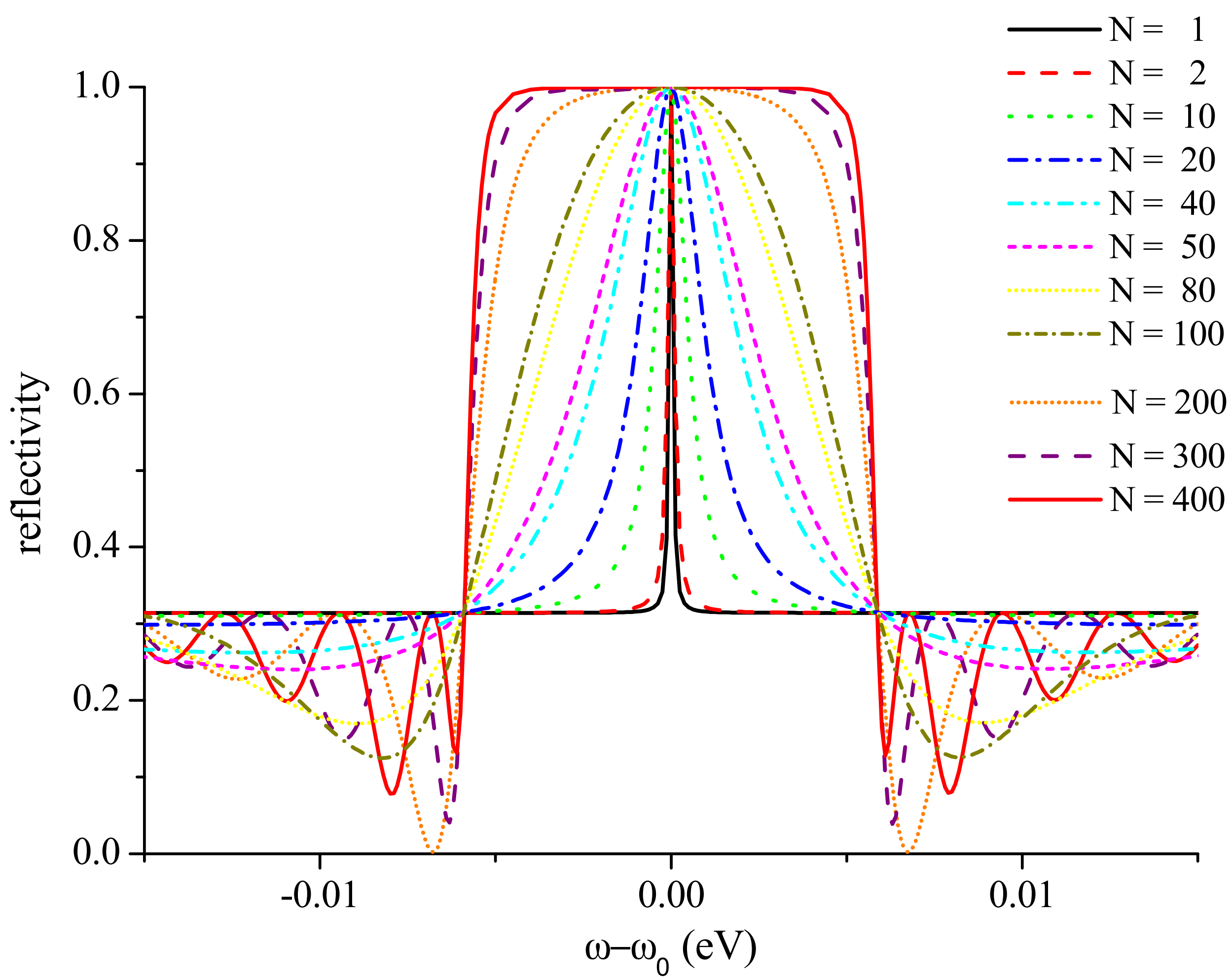
Periodic structures

MQW: super-radiant regime

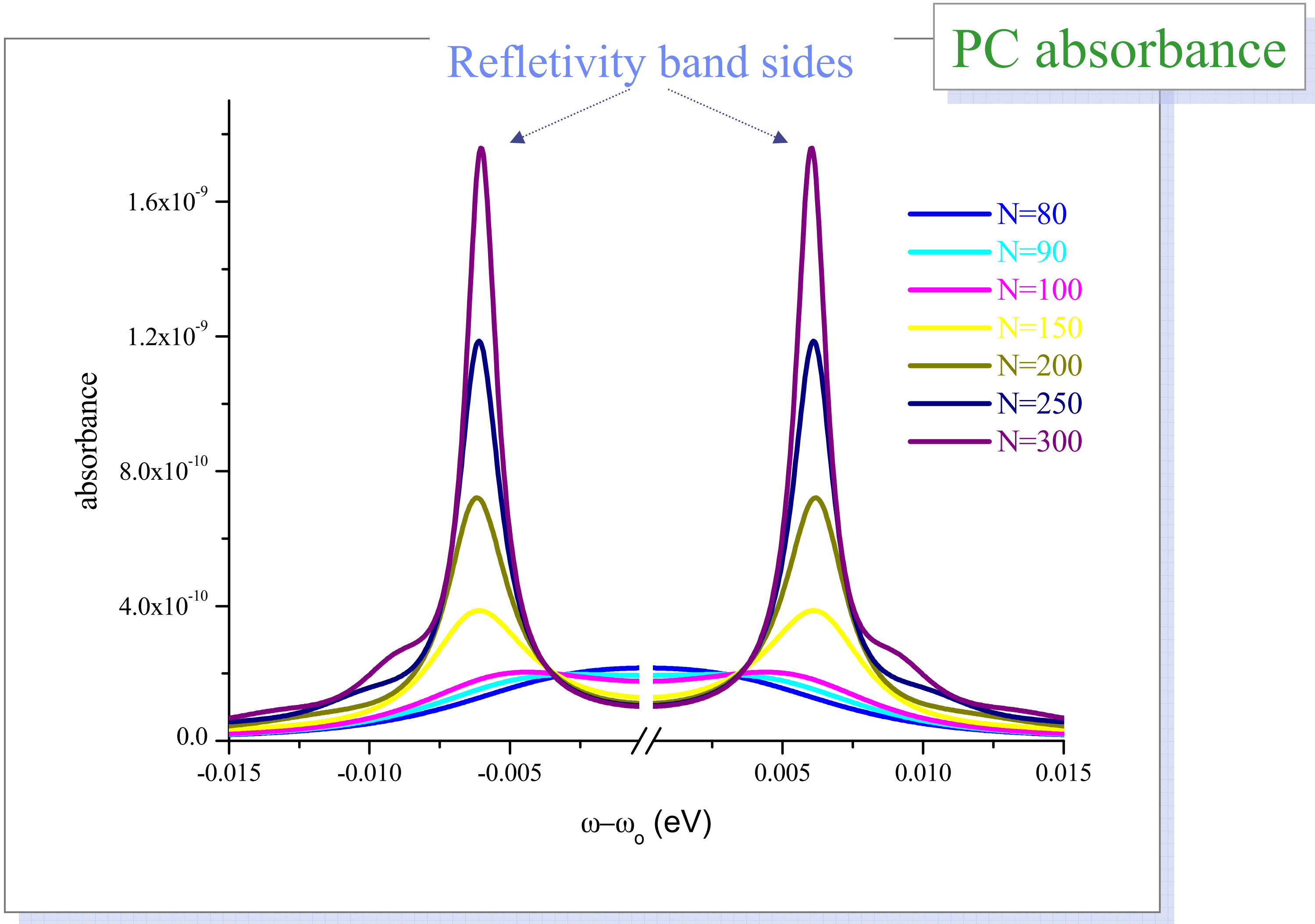


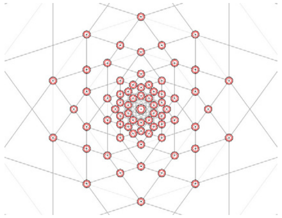
MQW: polaritonic crystal regime

PC reflectivity



MQW: polaritonic crystal regime

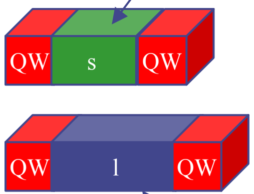




QW Fibonacci chains: scaling and fractals

short inter-well distance

F_1, F_2



} building bloks

long inter-well distance

golden ratio

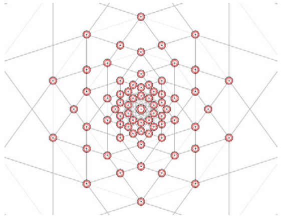
$$\ell / s = \frac{\sqrt{5}+1}{2}$$

$$F_{j+1} = F_j \bigcup F_{j-1}$$

QW Fibonacci chain

Resonant Fibonacci quantum well structures in one dimension
A.N. Poddubny, L.Pilozzi, M.M.Voronov, E.L.Ivchenko, Phys.Rev. B **77**, 113306 (2008)
Exciton-polaritonic quasicrystalline and aperiodic structures
A.N. Poddubny, L.Pilozzi, M.M.Voronov, E.L.Ivchenko, Phys.Rev. B **80**, 115314 (2009)

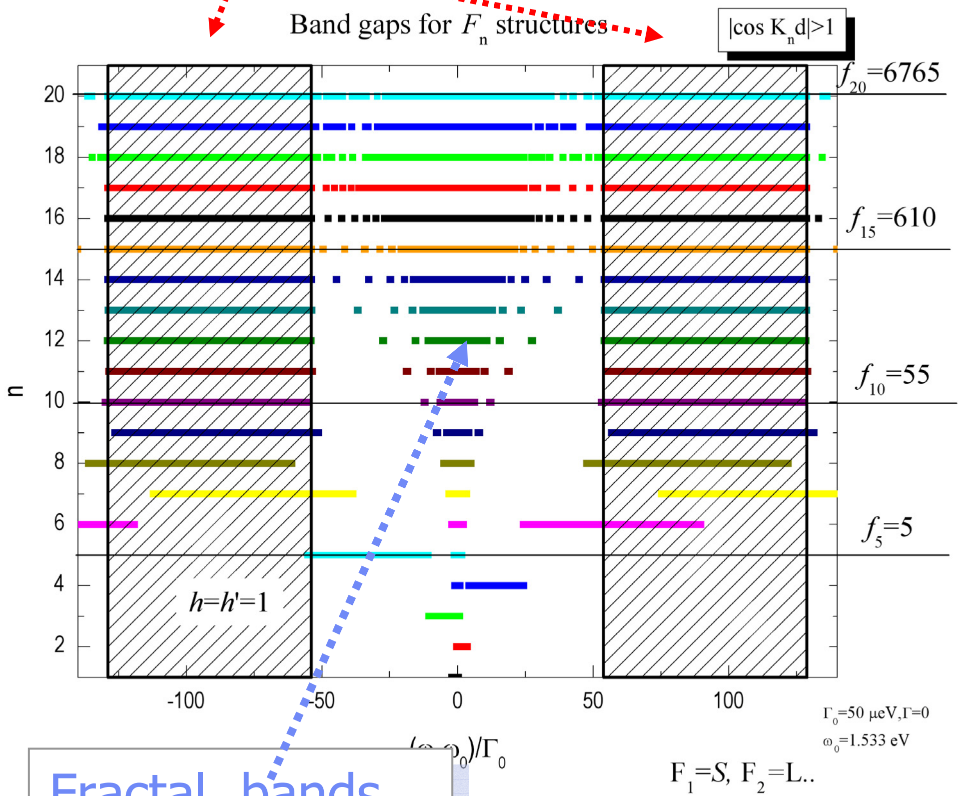
Quasicrystals



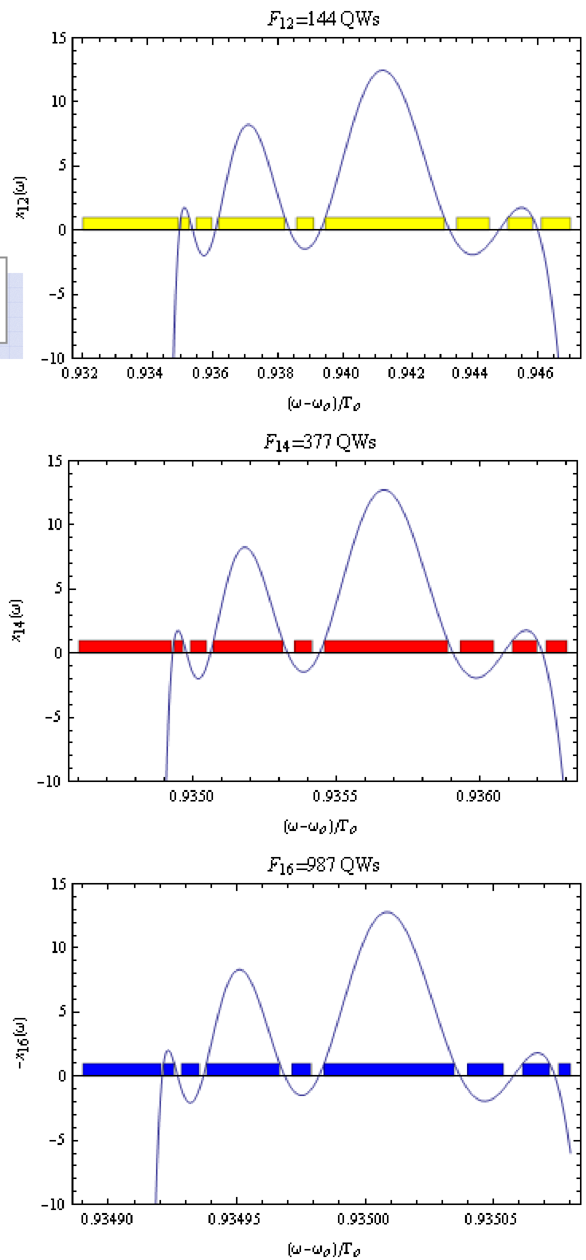
QW Fibonacci chain

Band scaling

polaritonic gaps



Fractal bands



EM field Green functions

Maxwell eqs.

$$\vec{\nabla}\times\vec{\nabla}\times\vec{E}(\vec{r},\omega)-q^2\vec{E}(\vec{r},\omega)=4\pi q^2\left[\vec{P}_b(\vec{r},\omega)+\vec{P}_x^1(\vec{r},\omega)+\vec{P}'(\vec{r},\omega)\right]$$

macroscopic r-dependence

microscopic r-dependence

$$q=\frac{\omega}{c}$$

$$\vec{P}_b(\vec{r},\omega)=\chi_b(\vec{r},\omega)\vec{E}(\vec{r},\omega)$$

$$\vec{P}_x^1(\vec{r},\omega)=\sum_\mu\frac{P_{o\mu}(\vec{r})}{E_{\mu o}-\hbar\omega-i\gamma}\int dr'P_{o\mu}(\vec{r}')E(\vec{r}',\omega)$$

P' remaining part of induced polarization

Kikuo Cho

"*Reconstruction of Macroscopic Maxwell Equations*" Springer Tracts. **237** (2010)

"*Optical Response of Nanostructures: Microscopic Nonlocal Theory*" Springer (2003)

EM field Green functions

Different ways to renormalize the Green function:

1) Green function for vacuum

$$\left[\vec{\nabla}\times\vec{\nabla}\times - q^2\overleftrightarrow{I}\right]\overleftrightarrow{G}_{vac}(\vec{r},\vec{r}\,',\omega) = 4\pi\overleftrightarrow{I}\,\delta(\vec{r}-\vec{r}\,')$$

No polarization is normalized into EM field

$$E(\vec{r},\omega) = E_o(\vec{r},\omega) + \int \overleftrightarrow{G}_{vac}(\vec{r},\vec{r}\,',\omega)P(\vec{r}\,',\omega)d\vec{r}\,'$$

incident field in vacuum

polarization induced field

2) Cavity Green function

Only background polarization is renormalized

$$\vec{\nabla}\times\vec{\nabla}\times\overleftrightarrow{g}(\vec{r},\vec{r}\,',\omega)-q^2\{1+4\pi\chi_b(\vec{r},\omega)\}\overleftrightarrow{g}(\vec{r},\vec{r}\,',\omega)=4\pi q^2\,\overleftrightarrow{I}\,\delta(\vec{r}-\vec{r}\,')$$

$$E(\vec{r},\omega)=E_o^{cav}(\vec{r},\omega)+\int\overleftrightarrow{g}(\vec{r},\vec{r}\,',\omega)\left[\vec{P}_x^1(\vec{r},\omega)+\vec{P}\,'(\vec{r},\omega)\right]d\vec{r}\,'$$

General shaped superstructure

EM Green function with nonlocal renormalization of background dielectrics

$$\vec{\nabla}\times\vec{\nabla}\times\vec{g}(\vec{r},\vec{r}\,',\omega) - q^2\{1+4\pi\chi_b(\vec{r},\omega)\}\vec{g}(\vec{r},\vec{r}\,',\omega) = 4\pi q^2\,\vec{I}\,\delta(\vec{r}-\vec{r}\,')$$

a) Non-local form of the background local polarization

$$\vec{P}_b(\vec{r},\omega) = \chi_b(\vec{r},\omega)\int d^3r'\,\delta(\vec{r}-\vec{r}\,')\,\vec{E}(\vec{r}\,',\omega)$$

b) Degenerate kernel

$$\delta(\vec{r}-\vec{r}\,') = \sum_\nu \phi_\nu^*(\vec{r})\,\phi_\nu(\vec{r}\,')$$

$$\vec{P}_b(\vec{r},\omega) = \sum_\nu \chi_{b\nu}(\vec{r},\omega)\,\phi_\nu^*(\vec{r})\int d^3r'\,\phi_\nu(\vec{r}\,')\,\vec{E}(\vec{r}\,',\omega)$$

3) Green function of cavity polariton

we include the linear polarization

$$\left[\vec{\nabla}\times\vec{\nabla}\times - q^2\varepsilon_b(\vec{r},\omega)I\right]\overleftrightarrow{G}_{cp}(\vec{r},\vec{r}\,',\omega) - \sum_{\mu}\frac{4\pi q^2 P_{o\mu}(r)}{E_{\mu o} - \hbar\omega - i\gamma}H_{\mu o}(r',\omega) = 4\pi q^2\,\overleftrightarrow{I}\,\delta(\vec{r}-\vec{r}\,')$$

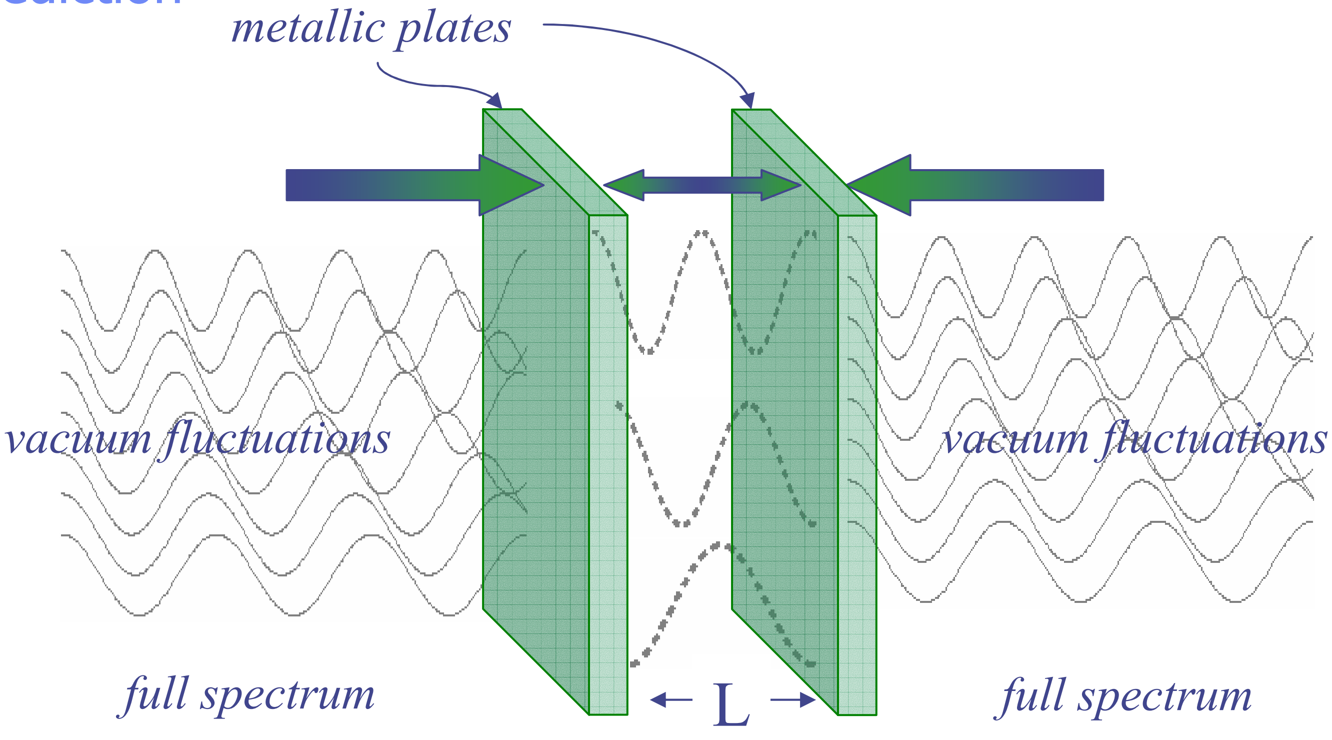
$$H_{\mu o}(r,\omega) = \int dr'' P_{\mu o}(r'',\omega) G_{cp}(\vec{r},\vec{r}\,',\omega)$$

$$\overleftrightarrow{G}_{cp}(\vec{r},\vec{r}\,',\omega) = g(\vec{r},\vec{r}\,',\omega) + \sum_{\mu}\frac{h_{o\mu}(r,\omega)}{E_{\mu o} - \hbar\omega - i\gamma}H_{\mu o}(r',\omega)$$

field induced by $P_{o\mu}(r)$ in the empty cavity

$$h_{o\mu}(r,\omega) = \int dr' g(\vec{r},\vec{r}\,',\omega) P_{o\mu}(r',\omega)$$

- Prediction



$\lambda < L$

H. B. G. Casimir, *Proc. K. Ned. Akad. Wet.* **51**(1948) 793

Zero point energy modification of the radiation field can produce an attractive force between neutral conductors.

$$F(L)/A = -\frac{\partial U(L)}{\partial L}\frac{1}{A} = \frac{\pi^2 \hbar c}{240 L^4}$$

1 atmosphere for L=10 nm

EM field Green functions → Casimir effect

- Change in e.m. field boundary conditions induces change in mode frequencies and then in the zero point energy:

$$E = \sum_n \frac{1}{2}\hbar\omega_n \qquad \omega_n = c\sqrt{k_{//}^2 + \frac{\pi^2}{L^2}n^2}$$

$$E(L) = \frac{\hbar c A}{\pi}\sum_{n=0}^{\infty} 2\pi\int_0^{\infty} k_{//}dk_{//}\sqrt{k_{//}^2 + \frac{\pi^2}{L^2}n^2} \qquad U(L) = E(L) - E(\infty) = -\frac{\pi^2\hbar c}{720L^3}A$$

- Casimir Forces as e.m. stress energy tensor can be obtained via Fluctuation-Dissipation theorem from the imaginary-frequency ($\omega = iw$) Green's function.

$$\left\langle E_j(\vec{x})E_k(\vec{x}\,')\right\rangle = \frac{\hbar}{\pi}w^2 G_{jk}(iw, \vec{x} - \vec{x}\,')$$

Measurements

- Marcus Sparnaay at Philips in Eindhoven, in 1958 confirmed the Casimir force existence but was not able to reach sufficient accuracy

- 1996 Steve K. Lamoreaux
  Los Alamos National Laboratory

  "*Demonstration of the Casimir Force in the 0.6 to 6 μm Range*"
  Phys. Rev. Lett. **78**, 5–8 (1997)

  measurement agreement with theory 10%

- 1997 Umar Mohideen and Anushree Roy
  University of California at Riverside

  "*Precision Measurement of the Casimir Force from 0.1 to 0.9 μm*"
  Phys. Rev. Lett. **81**, 004549 (1997)

  measurement agreement with theory 1%

institute for complex systems

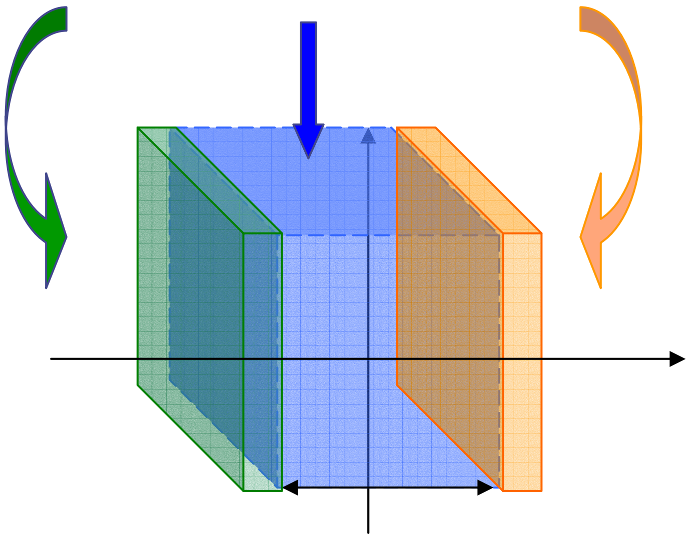
Casimir effect

Material design for force control: crossover from attraction to repulsion

As shown theoretically in a seminal paper by Evgeny Lifshitz

in certain circumstances repulsive forces can arise

$$\varepsilon_1(\omega) > \varepsilon_3(\omega) > \varepsilon_2(\omega)$$



Casimir repulsion experimentally demonstrated in Gold-Bromobenzene-Silicon

nature Vol 457|8 January 2009|doi:10.1038/nature07610

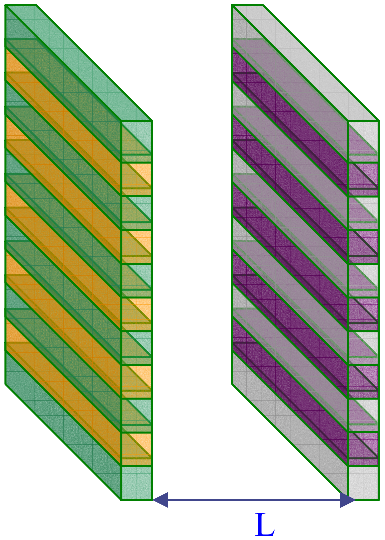
LETTERS

Measured long-range repulsive Casimir–Lifshitz forces

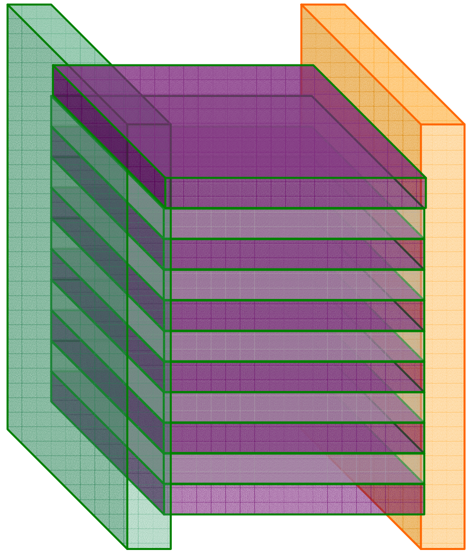
J. N. Munday[1], Federico Capasso[2] & V. Adrian Parsegian[3]

Can geometry alone
give rise to Casimir repulsion?

Casimir force tailoring by complex asymmetric cavity geometries



Patterned mirrors



Patterned cavity

- numerical approach
  Imaginary-frequency scattering-matrix techniques

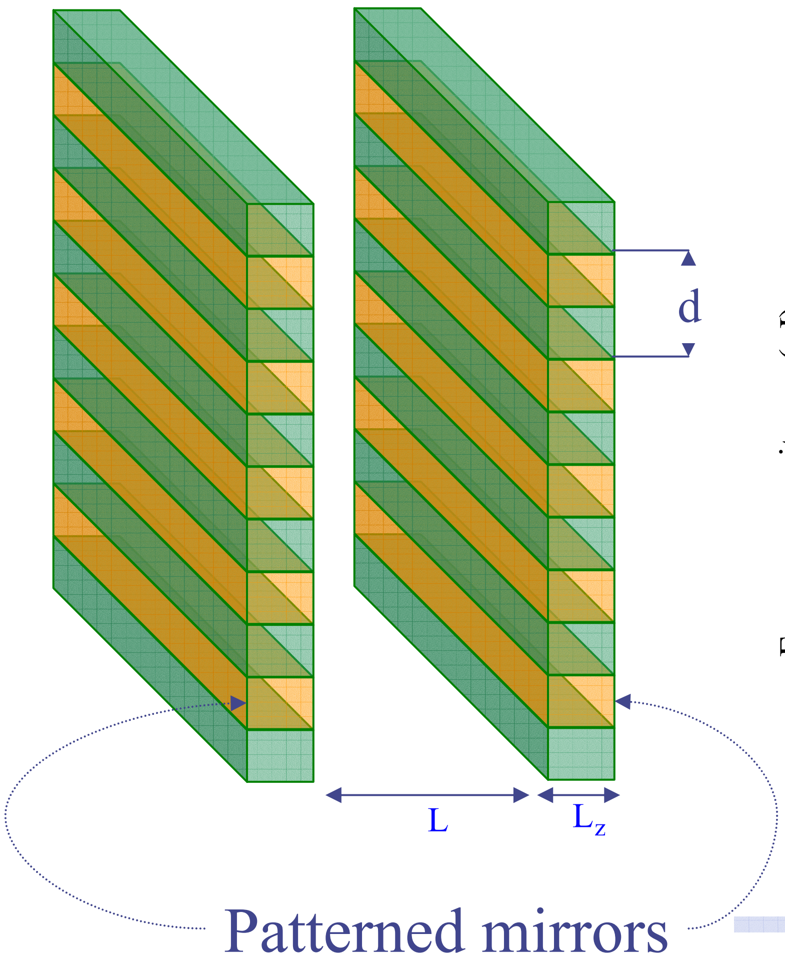
$$P(d) = 2k_B T \sum_{n=0}^{\infty}{}' \int_0^{\infty} \frac{d^2\vec{q}_{//}}{2\pi} q_z(iw_n) \sum_{\alpha=S,P} \frac{r_\alpha^{(1)}(iw_n)\, r_\alpha^{(2)}(iw_n)\, e^{-2q_z d}}{1 - r_\alpha^{(1)}(iw_n)\, r_\alpha^{(2)}(iw_n)\, e^{-2q_z d}}$$

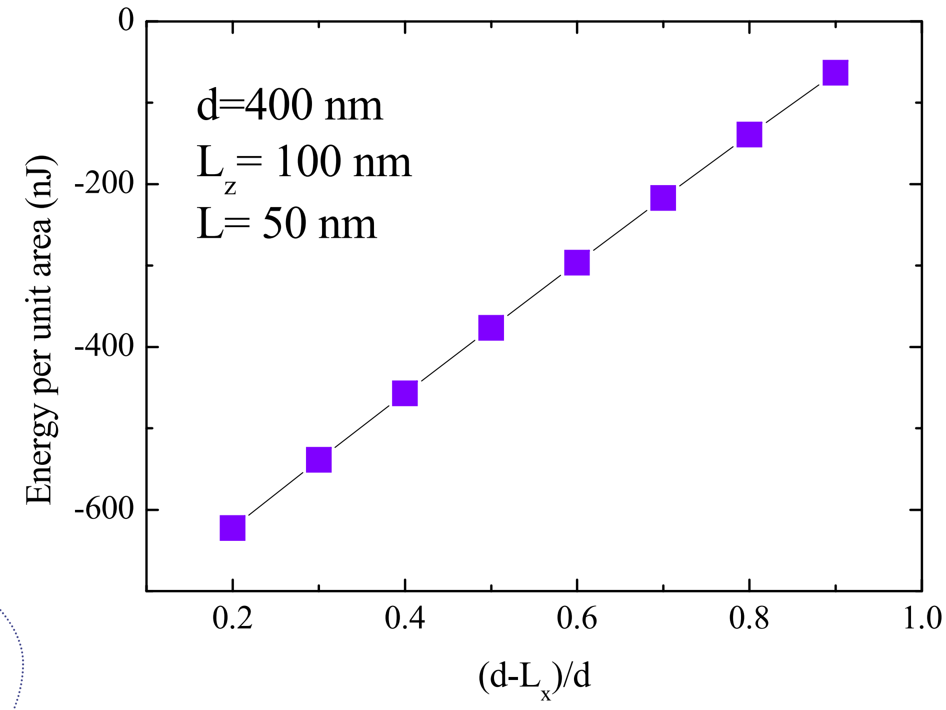
$$r_S^{\mu}(iw_n) = \frac{q_z - k_z^{\mu}}{q_z + k_z^{\mu}} \qquad r_P^{\mu}(iw_n) = \frac{\varepsilon_o k_z^{\mu} - q_z\, \varepsilon^{\mu}(iw_n)}{\varepsilon_o k_z^{\mu} + q_z\, \varepsilon^{\mu}(iw_n)} \qquad w_n = 2\pi \frac{k_B T}{\hbar} n$$

For patterned systems

$$P(L,T) = -k_B T \frac{\partial}{\partial L} \sum_{n=0}^{\infty}{}' \int_0^{\infty} \frac{d^2\vec{q}_{//}}{2\pi} \ln\det\left[\overleftrightarrow{I} - \overleftrightarrow{r}_1(iw_n)\, \overleftrightarrow{\chi}^{>}(L)\, \overleftrightarrow{r}_2(iw_n)\, \overleftrightarrow{\chi}^{>}(L) \right]$$

Casimir force tailoring by complex asymmetric cavity geometries

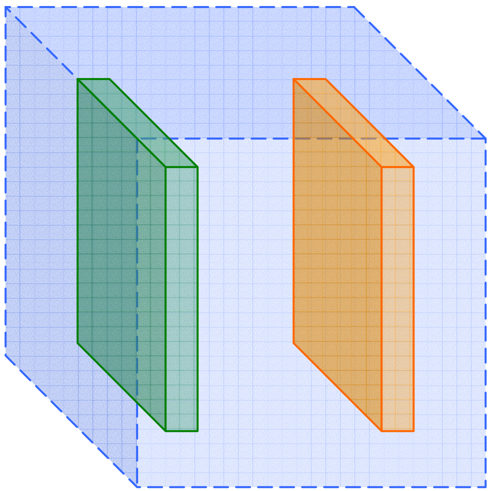


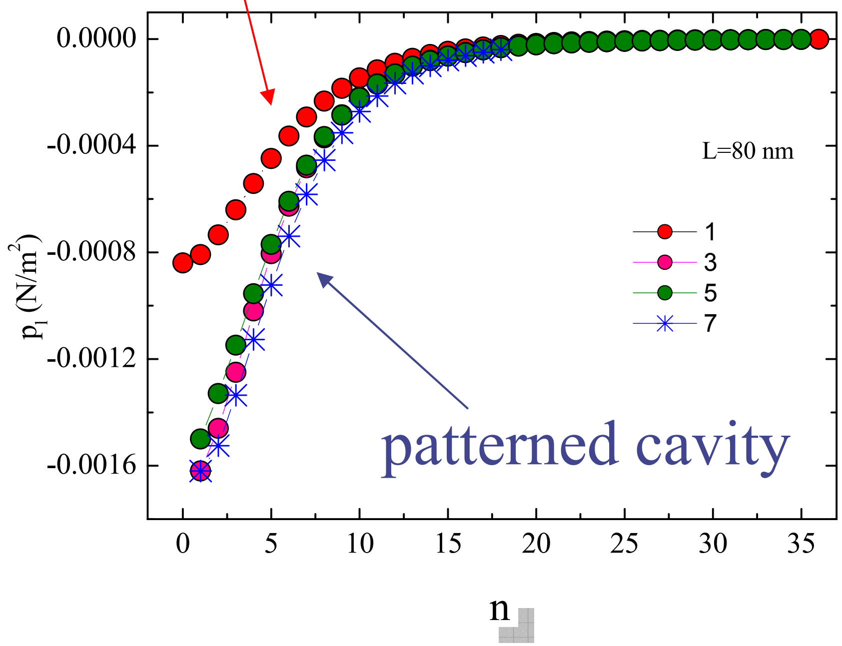


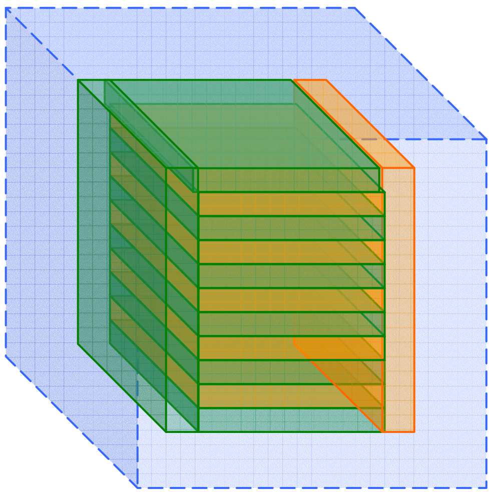
Casimir force tailoring by complex asymmetric cavity geometries

single Matsubara frequency contributions

homogeneus cavity







patterned cavity

Matsubara frequency $w_n = 2\pi \frac{k_B T}{\hbar} n$

Conclusions

- We have discussed the optical properties of periodic and aperiodic polaritonic crystals and have shown how a particular renormalization of the Green function allows to consider more complex geometries.

- This renormalization is the required tool to consider complex geometries for the Casimir force tailoring

since

- this force can be computed as an integral of the mean electromagnetic stress tensor over all the frequencies, determined from the classical Green function as a consequence of the fluctuation-dissipation theorem.