Topological states of interacting light, sound and excitons

with multiple quantum wells

Alexander Poddubny

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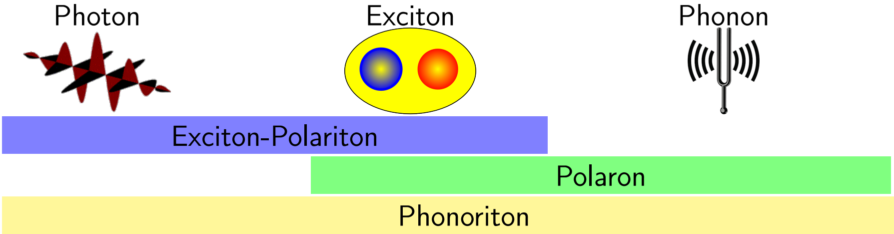
Physics of Exciton-Polaritons in Artificial Lattices

Daejeon, Korea, May 2017

Introduction

Goals: control of light by sound and sound by light

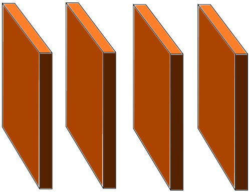
Ingredients:



Platform: multiple-quantum-well structures

Advantages:

- easy scalable down to thicknesses ~ 10 nm
- mature planar fabrication technology
- resonant enhancement of optomechanical interaction
- easy integrable with existing optoelectronics

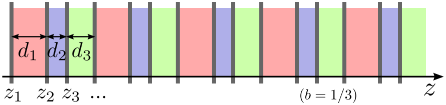


Outline

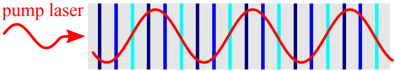
Topological Polaritonic Crystal

Poshakinskiy, ANP, Pilozzi, Ivchenko, PRL **112**, 107403 (2014)

Poshakinskiy, ANP, Hafezi, PRA **91**, 043830 (2015)



Optically-induced Topological Acoustic Crystal

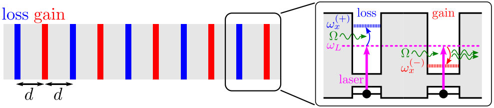


Optically-Controlled Acoustic Laser with Parity-Time Symmetry

ANP, Poshakinskiy, Jusserand, Lemaître, PRB **89**, 235313 (2014)

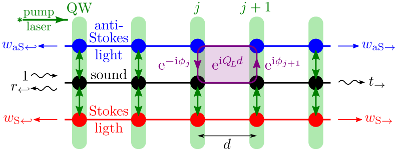
Jusserand, ANP, Poshakinskiy, Fainstein, Lemaître, PRL **115**, 267402 (2015)

Poshakinskiy, ANP, A. Fainstein, PRL **117**, 224302 (2016)



Phonoritonic Crystal with a Synthetic Magnetic Field for an Acoustic Diode

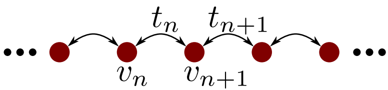
Poshakinskiy, ANP, PRL **118**, 156801 (2017)



Introduction: Aubry-André-Harper (AAH) model

Tight-binding Hamiltonian
for the 1D lattice

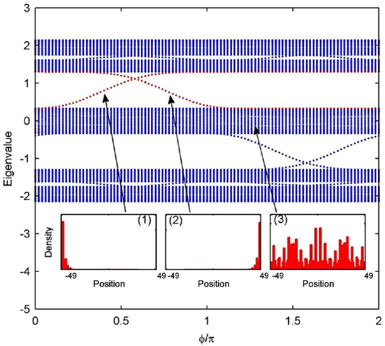
$$\langle n|H|n\rangle = v_n$$
$$\langle n+1|H|n\rangle = t_n$$



In Aubry-André-Harper model
the on-site potential v_n
or tunneling strength t_n
are spatially modulated:

$$v_n = v\cos(2\pi bn + \phi_v)$$
$$t_n = t[1 + \eta\cos(2\pi bn + \phi_t)]$$

Energy spectra
as a function of modulation phase



Aubry, André, Annals of Israel Physical Society 3, 133 (1979)
Lang, Cai, Chen, PRL **108**, 220401 (2012)
Kraus, Lahini, Ringel, Verbin, Zilberberg, PRL **109**, 106402 (2012)
Ganeshan, Sun, Das Sarma, PRL **110**, 180403 (2013)

Resonant photonic AAH crystal

Resonant light reflection from a quantum well (QW)

$$r(\omega) = -\frac{\mathrm{i}\Gamma_0}{\omega - \omega_0 + \mathrm{i}(\Gamma_0 + \Gamma)}$$

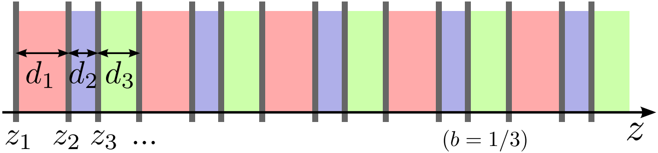
ω_0 – exciton resonance frequency
Γ_0 – exciton radiative decay
Γ – exciton non-radiative decay

We consider a multiple-QW structure
where the inter-QW distances are AAH-modulated:

$$d_n = z_{n+1} - z_n = d[1 + \eta \cos(2\pi b n + \phi)]$$

The primary period d satisfies the **resonant Bragg condition** $\omega_0\sqrt{\varepsilon}d/c = \pi$

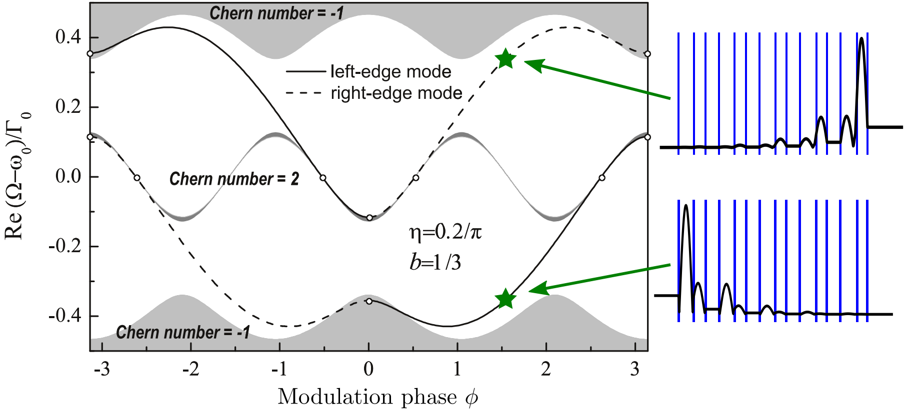
Structure is **periodic** for rational b and **quasicrystalline** for irrational b



Key differences from the standard electron problem:

- long range coupling between the layers (via light)
- the system is open (light can escape through edges)

Chern numbers & edge states



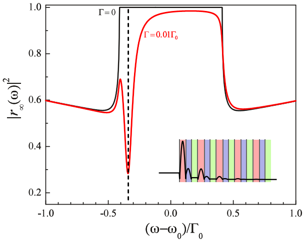
Contrary to the conventional electronic topological states, the optical edge modes are radiative; i.e., they decay in time due to the **light escape through the structure boundaries**

Poshakinskiy, ANP, Pilozzi, Ivchenko, Phys. Rev. Lett. 112, 107403 (2014)

Detection of optical edge states

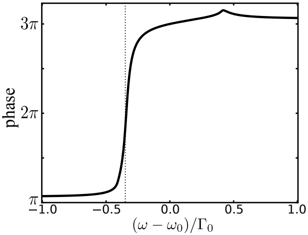
Radiative **state** $\Leftrightarrow$ **pole** of the reflection coefficient $r(\omega)$

Reflection coefficient



Dip in reflectivity

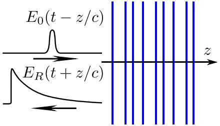
Reflection phase



Phase change by 2π

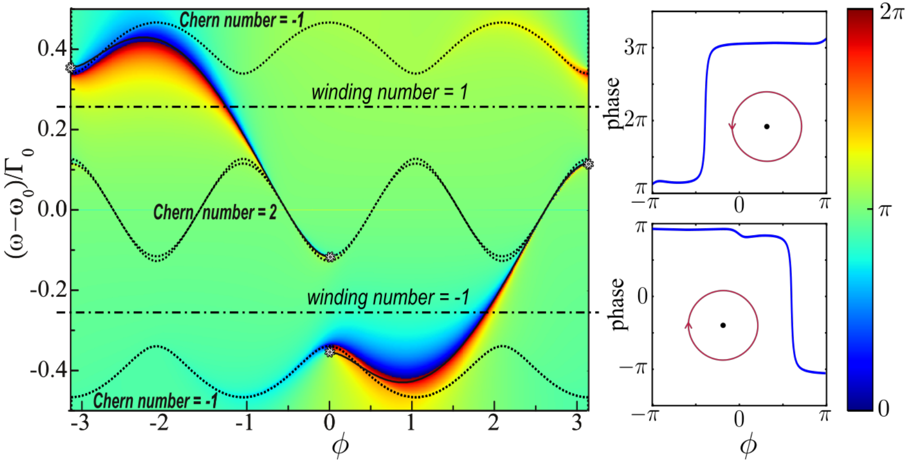
Short pulse response

$$\rho(t) = \int_{-\infty}^{+\infty} r(\omega)\, \mathrm{e}^{-\mathrm{i}\omega t} \frac{d\omega}{2\pi}$$



Exponential contribution $\rho(t) \propto \exp(-\mathrm{i}\Omega t)$

Light reflection phase and topological indexes

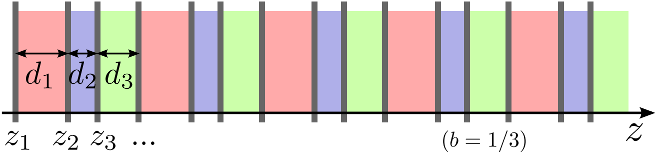


- (Phase winding # of a band gap) = (# of edge states crossing the gap)
- (Chern # of a band) = (upper-gap winding #) − (lower-gap winding #)
- (Chern #) = (# of phase branching points/reflection coefficient zeros)

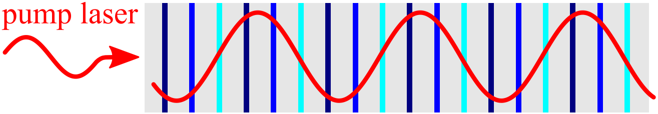
Poshakinskiy, ANP, Hafezi, PRA **91**, 043830 (2015)

Outline

- Topological Polaritonic Crystal

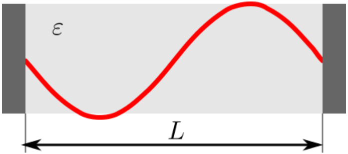


- Optically-induced Topological Acoustic Crystal



- Optically-Controlled Acoustic Laser with Parity-Time Symmetry
- Phonoritonic Crystal with a Synthetic Magnetic Field for an Acoustic Diode

Optomechanic coupling: geometric vs photoelastic



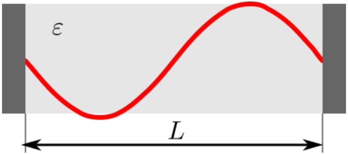
Cavity resonance:

$$\omega = \frac{N\pi c}{L\sqrt{\varepsilon}}$$

Coupling constant: $g_{\rm om} \equiv \frac{{\rm d}\omega}{{\rm d}u} = -\frac{\omega}{L} - \frac{\omega}{2}\frac{1}{\varepsilon}\frac{{\rm d}\varepsilon}{{\rm d}u}$

geometric term — photoelastic term

Optomechanic coupling: geometric vs photoelastic



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geometric term — photoelastic term

Photoelastic tensor : $p_{\alpha\beta\gamma\delta} = -\frac{1}{\varepsilon_{\alpha\beta}\varepsilon_{\gamma\delta}}\frac{\partial \varepsilon_{\alpha\beta}}{\partial u_{\gamma\delta}}$

modification of permittivity by deformation

$$\frac{g_{\rm om}^{\rm (el)}}{g_{\rm om}^{\rm (geom)}} \sim p\frac{\lambda_{\rm photon}}{\lambda_{\rm phonon}}$$

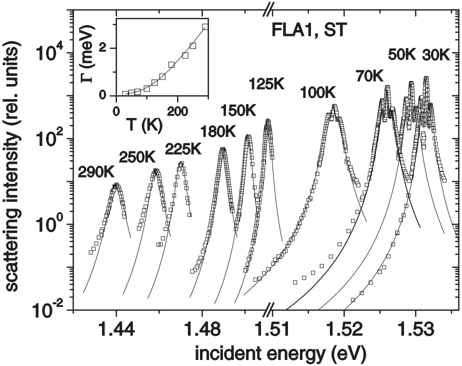
Light-sound interaction is characterized by the photoelastic coefficient

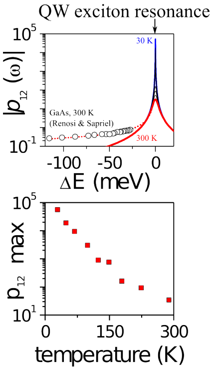
$$p_{12}(\omega) = -\frac{1}{\varepsilon^2}\frac{\partial \varepsilon_{xx}(\omega)}{\partial u_{zz}} \sim \frac{\Gamma_0 \Xi}{(\omega - \omega_0 + \mathrm{i}\Gamma)^2}$$

u_{zz} is deformation

$\Xi \sim 10\,\mathrm{eV}$ is the deformation potential constant

Coefficient p_{12} is readily accessible from the **Brillouin scattering**



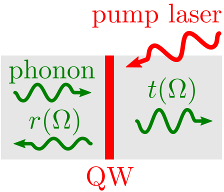


Photoelastic coefficient reaches 10^5 at the exciton resonance

Jusserand, ANP, Poshakinskiy, Fainstein, Lemaître, PRL 115, 267402 (2015)

Optomechanical effects in laser-pumped QWs

Sound reflection and transmission through a **laser-pumped** QW

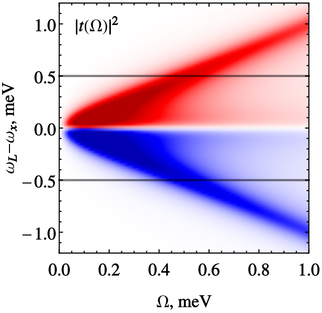


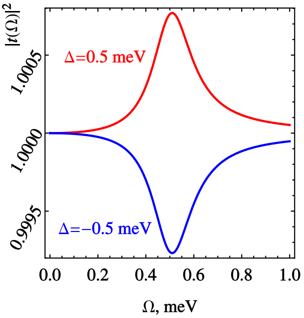
$$r(\Omega) = \frac{\mathrm{i}\gamma \,\mathrm{sign}\,\Delta}{|\Delta| - \Omega + \mathrm{i}(\Gamma_x - \gamma\,\mathrm{sign}\,\Delta)}; \qquad t(\Omega) = 1 - r(\Omega)$$

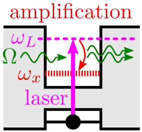
$\Delta = \omega_L - \omega_x$ is laser detuning; Γ_x is the exciton decay rate

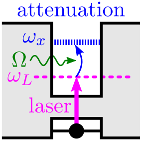
$\gamma = \dfrac{n_x \Xi^2 \Omega}{2\rho s^3} \sim 1\,\mu\mathrm{eV}$ is proportional to the laser-generated coherent exciton population n_x

Optomechanical heating & cooling





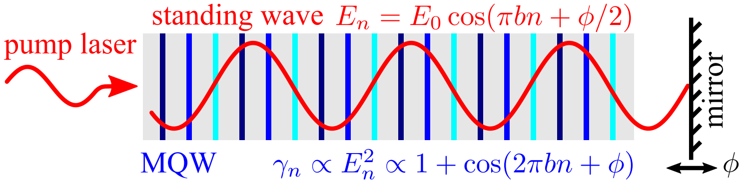




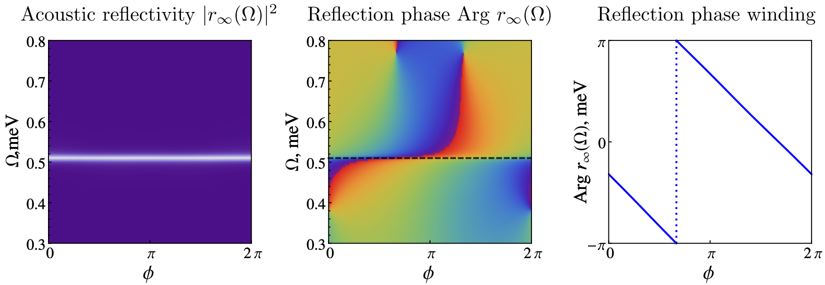
Poshakinskiy, ANP, A. Fainstein, PRL **117**, 224302 (2016)

Optically-induced acoustic AAH crystals

Pump laser creates spatial (quasi)periodic modulation of exciton density



Both the period (laser frequency) and the phase (mirror position) of the modulation are **easily controlled**



Outline

- Topological Polaritonic Crystal
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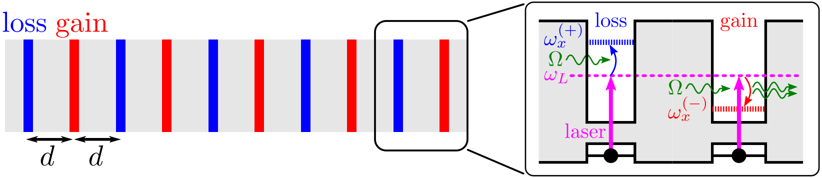
- Optically-Controlled Acoustic Laser
  with Parity-Time Symmetry



- Phonoritonic Crystal with a Synthetic Magnetic Field
  for an Acoustic Diode

$\mathcal{PT}$-symmetric systems

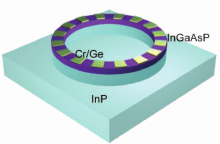
$\mathcal{PT}$ = spatial inversion + complex conjugation

System invariant under such operation can have **real spectrum** (but not always)

- $\mathcal{PT}$-symmetry in quantum mechanics:
  Hamiltonian $\hat{H}$ is not Hermitian, but $\hat{H}(-x) = \hat{H}^\dagger(x)$;
  e.g., $\hat{H} = \hat{p}^2/(2m) - (\mathrm{i}x)^n$
  C.M. Bender, S. Boettcher, PRL **80**, 5243 (1998)

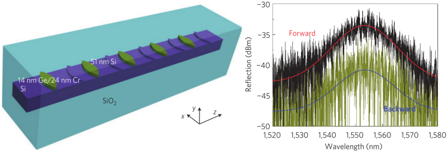
- $\mathcal{PT}$-symmetry in optics: $\varepsilon(-\boldsymbol{r}) = \varepsilon^*(\boldsymbol{r})$
  Rüter *et al*, Nat. Phys. **6**, 192 (2010)

Single-mode lasing



L. Feng *et al*, Science **346**, 972 (2014)

Unidirectional reflectionless



L. Feng *et al*, Nat. Mat. **12**, 108 (2013)

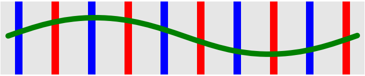
- $\mathcal{PT}$-symmetry in acoustics: **not yet realized at nanoscale**
  Zhu, Ramezani, Shi, Zhu, Zhang, "$\mathcal{PT}$-symmetric acoustics", PRX **4**, 031042 (2014)
  Shi, Dubois,Chen,Cheng, Ramezani, Wang, Zhang, Nat. Commun. **7**, 11110(2016)

Breaking of $\mathcal{PT}$-symmetry near Bragg resonance

Sound dispersion in $\mathcal{PT}$-symmetric structure

$$\Omega(K) = \Omega_0 \pm \sqrt{s^2 \left(K - \frac{\pi}{2d}\right)^2 - G^2}$$

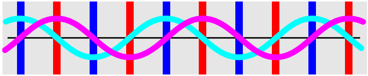
$\mathcal{PT}$-symmetry **holds**



Bloch modes interacts equally with amplifying and attenuating QWs

$\Omega(K)$ are real

$\mathcal{PT}$-symmetry **is broken**



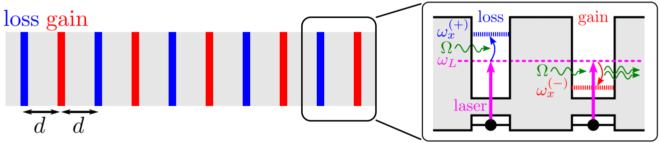
Standing wave with the Bloch vector $\pi/2d$ interacts either with amplifying, or with attenuating QWs

$\Omega(K)$ are complex

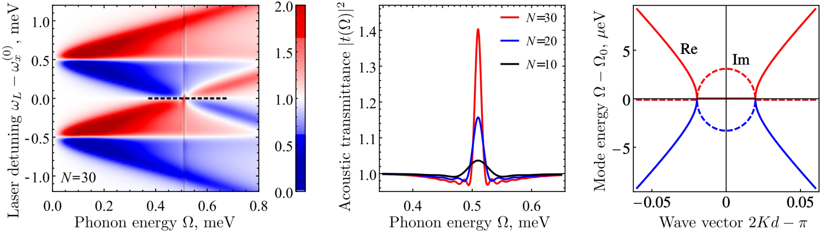
$\mathcal{PT}$-symmetry is broken
in a **very narrow** range of wave vectors $\left|K - \frac{\pi}{2d}\right| < G$

Parity-time symmetric acoustic crystal

Structure with the unit cell containing two QWs
with exciton frequencies $\omega_x^{(\pm)} = \omega_x^{(0)} \pm \delta\omega_x$



When the pump laser frequency is in the middle of two exciton resonances, gain and loss are balanced, so acoustic parity-time ($\mathcal{PT}$) symmetry arises



Structure acts as a highly-selective acoustic amplifier and can be used to build a single-mode phonon laser

Poshakinskiy, ANP, A. Fainstein, PRL **117**, 224302 (2016)

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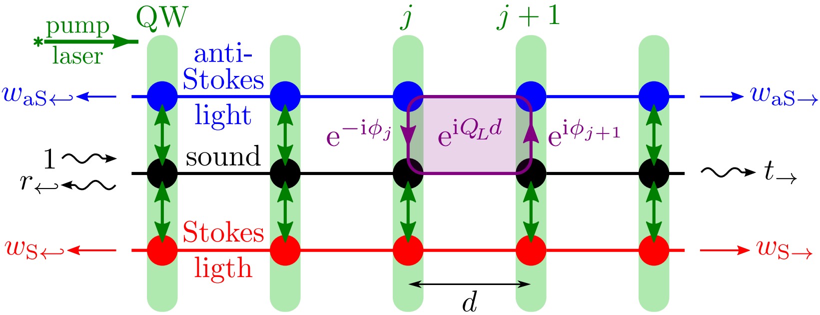
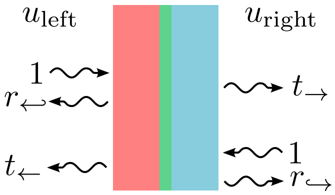


Reciprocity

Linear response of the optical or acoustic field $u(z,t)$

$$u_{\rm left}^{\rm (out)} = r_{\hookleftarrow} u_{\rm left}^{\rm (in)} + t_{\leftarrow} u_{\rm right}^{\rm (in)}$$

$$u_{\rm right}^{\rm (out)} = t_{\rightarrow} u_{\rm left}^{\rm (in)} + r_{\hookrightarrow} u_{\rm right}^{\rm (in)}$$



Onsager principle yields symmetry of the response functions

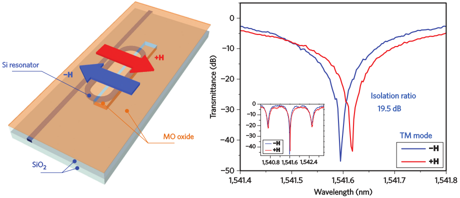
$$\boxed{t_{\rightarrow} = t_{\leftarrow}}$$ (but maybe $r_{\hookleftarrow} \neq r_{\hookrightarrow}$)

Onsager principle holds for

- linear response
- time-inversion-symmmetry
- and thermal equilibrium

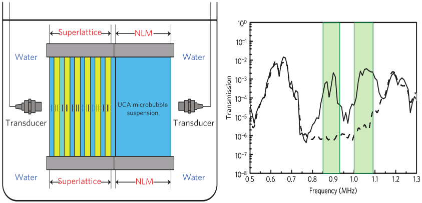
Maznev *et al*, Wave Motion **50**, 776 (2013)
Jalas *et al*, Nature Photon. **7**, 579 (2013)

External magnetic field



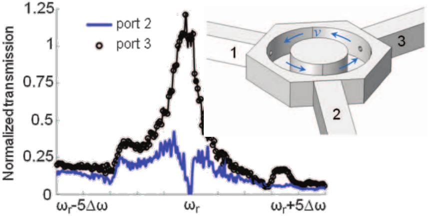
Bi *et al*, Nature Photonics **5**, 758 (2011)

Non-linear material



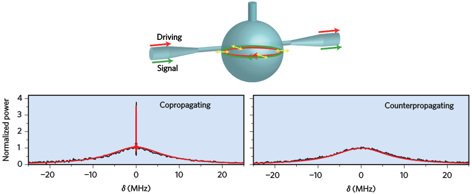
Liang *et al*, Nature Materials **9**, 992 (2010)

Mechanical rotation



Fleury *et al*, Science **343**, 516 (2014)

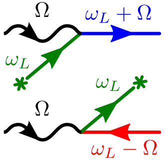
Coherent drive in optomechanics



Hafezi Rabl, Opt. Express **20**, 7672 (2012)
Shen et al, Nature Photonics **10**, 657 (2016)

For a quantum well under laser pump
sound can be converted to Stokes and anti-Stokes light

laser + phonon ↔ anti-Stokes photon

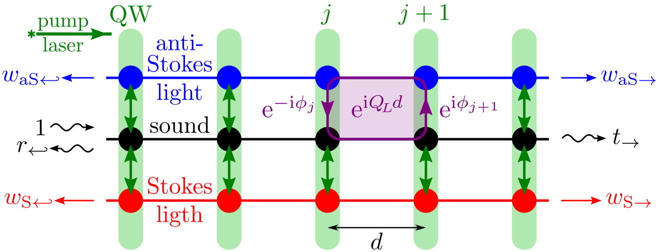


$$=\frac{e^{+i\phi_L}\sqrt{\gamma\Gamma_0}}{\Omega+i\Gamma_x+\Delta}$$

laser ↔ Stokes photon + phonon

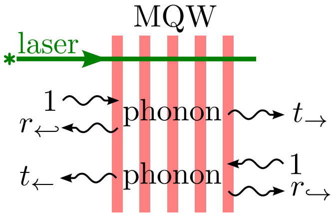
$$=\frac{e^{-i\phi_L}\sqrt{\gamma\Gamma_0}}{\Omega+i\Gamma_x-\Delta}$$

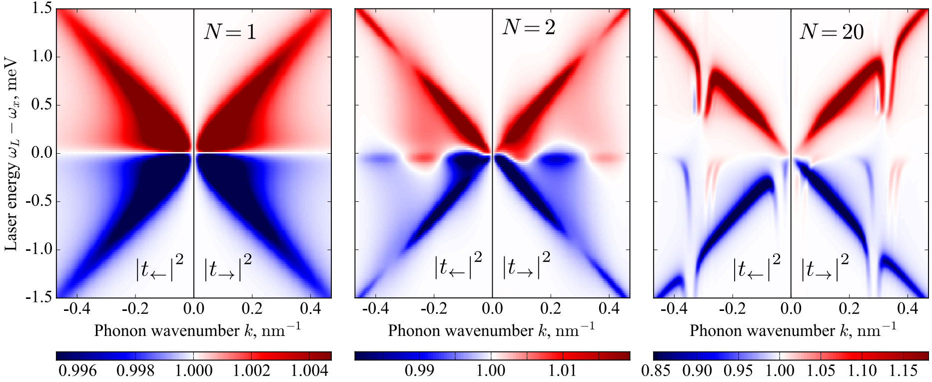
Propagation of coupled sound and light in a 1D structure is equivalent to quantum walks in a 2D $N\times 3$ lattice in an synthetic magnetic field



Nonreciprocal sound transmission

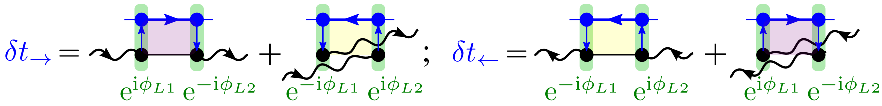
Map of sound transmission coefficients through N QWs from left to right ($t_{\rightarrow}$) and from right to left ($t_{\leftarrow}$)





Origin of nonreciprocity for two quantum wells

Contributions to $t_\rightarrow$ and $t_\leftarrow$ from **sound** $\rightarrow$ light $\rightarrow$ **sound** processes

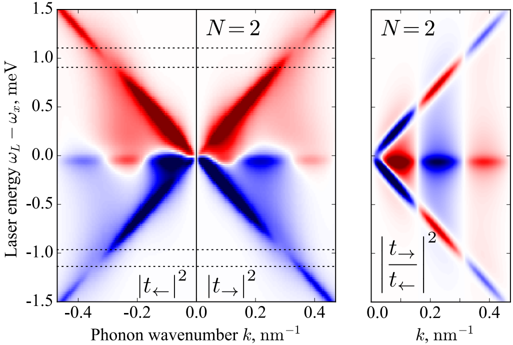


Conversion yields phase $\phi_{L2} - \phi_{L1} = q_L d$,
due to wave vector of the pump laser q_L

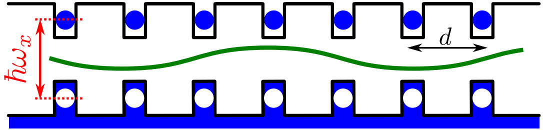
$$\delta t_{\rightarrow(\leftarrow)} = -\frac{\gamma\Gamma_0}{(\Delta+\Omega+i\Gamma)^2}\cos(k \pm q_L)d + \frac{\gamma\Gamma_0}{(\Delta-\Omega-i\Gamma)^2}\cos(k \mp q_L)d$$

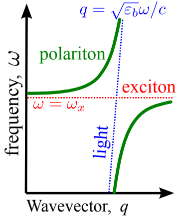
- Dip in amplification/attenuation for $k = \pi/d \pm q_L$
- Dip position for $t_\rightarrow$ and $t_\leftarrow$ is different by $2q_L$
- Transmission asymmetry

$$\left|\frac{t_\rightarrow}{t_\leftarrow}\right|^2 = 1 + 16\gamma\Gamma_0 \sin kd \sin q_L d \times \mathrm{Re}\frac{(\Omega+i\Gamma)^2+\Delta^2}{[(\Omega+i\Gamma)^2-\Delta^2]^2}$$



light + exciton = polariton

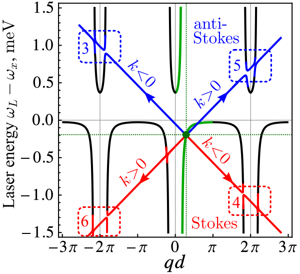




$Q = \frac{\omega}{c}\sqrt{\varepsilon_{\text{eff}}(\omega)}$ with $\varepsilon_{\text{eff}} = \varepsilon_b\left(1 + \frac{\omega_{\text{LT,eff}}}{\omega_0 - \omega - \text{i}\Gamma}\right)$

sound + polariton = *phonoriton*

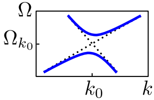
Thoery: Ivanov & Keldysh, JETP (1983), Keldysh & Tikhodeev, JETP (1986), Gippius *et al*, pss (b) (1990)
Experiment: Vygovskiĭ *et al*, JETP Lett. (1985), Hanke *et al*, PRL (1999)



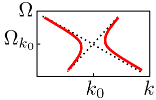
Phonoriton dispersion

$$\left[\varepsilon - \varepsilon_k^{(\text{polariton})}\right]\left[\varepsilon - \varepsilon_k^{(\text{phonon})}\right] = \delta^2$$

Energy avoided crossing ($\delta^2 > 0$)

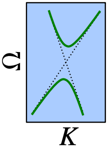


Wave vector avoided crossing ($\delta^2 < 0$)



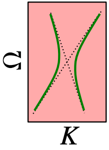
Manifestation of *phonoritons* in transmission spectra

Energy avoided crossing



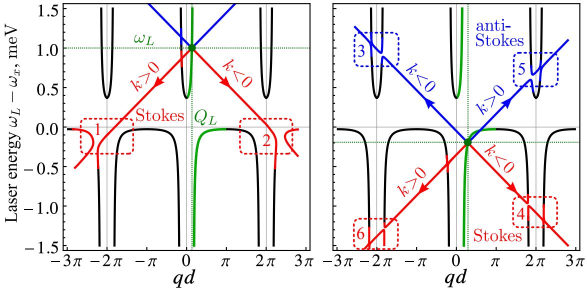
- band gap for energies
- real energies correspond to complex wave vectors
- attenuation of transmitted waves

Wave vector avoided crossing

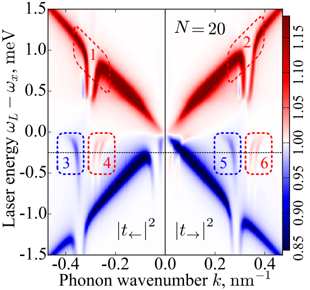


- band gap for wave vectors
- wave vectors correspond to complex energies
- amplification of transmitted waves

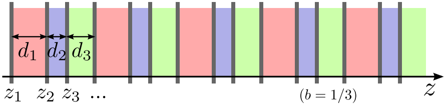
Phonoriton spectra



Acoustic transmittance



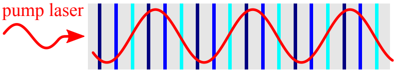
Topological Polaritonic Crystal



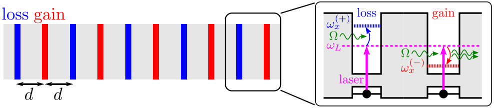
Poshakinskiy, ANP, Pilozzi, Ivchenko, PRL **112**, 107403 (2014)

Poshakinskiy, ANP, Hafezi, PRA **91**, 043830 (2015)

Optically-induced Topological Acoustic Crystal



Optically-Controlled Acoustic Laser with Parity-Time Symmetry

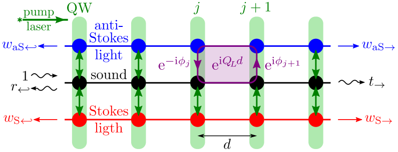


ANP, Poshakinskiy, Jusserand, Lemaître, PRB **89**, 235313 (2014)

Jusserand, ANP, Poshakinskiy, Fainstein, Lemaître, PRL **115**, 267402 (2015)

Poshakinskiy, ANP, A. Fainstein, PRL **117**, 224302 (2016)

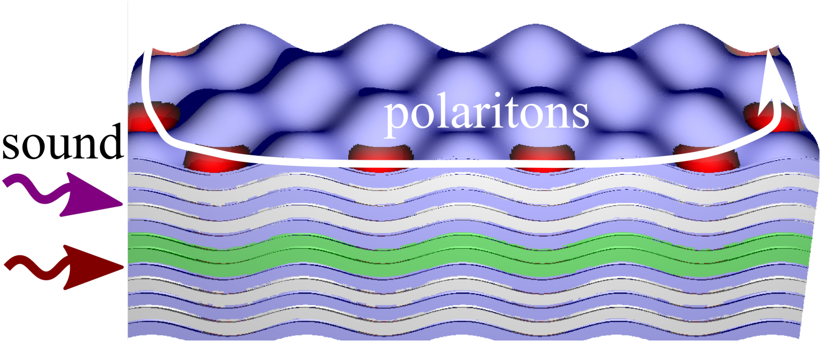
Phonoritonic Crystal with a Synthetic Magnetic Field for an Acoustic Diode



Poshakinskiy, ANP, PRL **118**, 156801 (2017)

Outlook

In-plane one-way transport of phonoritons in a cavity?



Experiment on trapping of polaritons by surface acoustic waves

de Lima, Hey, Santos, and Cantarero, PRL **94**, 126805 (2005)

Dissipative coupling and bistabilities for cavity polaritons:

Kyriienko, Liew, and Shelykh, PRL **112**, 076402 (2014)

Novel optomechanical interaction mechanisms:

Bobrovska, Matuszewski, Liew, and Kyriienko, PRB **95**, 085309 (2017)

Phase diagram of coupled light and matter

Regimes depending on exciton-photon and exciton-phonon coupling strength