Topological Phases of Sound and Light

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DARPA ORCHID
Cavity Optomechanics

Optomechanical Arrays

Topological Phases of Sound (and Light)

Dynamical Gauge Fields for the photons
baryon-photon fluid: sound speed $c/\sqrt{3}$
Radiation forces

- Optical tweezers
- Optical lattices

Trapping and cooling
\[ \hat{H} = \hbar \omega_{\text{cav}} \cdot (1 - \hat{x}/L) \hat{a}^\dagger \hat{a} + \hbar \Omega \hat{b}^\dagger \hat{b} + \ldots \]

\[ \hat{x} = x_{\text{ZPF}} (\hat{b} + \hat{b}^\dagger) \]

\[ x_{\text{ZPF}} = \sqrt{\hbar / 2m\Omega} \]
The zoo of experimental setups in cavity optomechanics, 2005-now

Karrai (Munich)
Bouwmeester (Santa Barbara)
Vahala (Caltech)
Mavalvala (MIT)
Kippenberg (EPFL), Carmon, ...
LKB group (Paris)
Painter (Caltech)
Lipson (Cornell)
Sillanpää (Aalto U)
Stamper-Kurn (Berkeley)

Harris (Yale)
Teufel, Lehnert (Boulder)
cold atoms
Fundamental tests of quantum mechanics in a new regime:
entanglement with ‘macroscopic’ objects, unconventional decoherence?
[e.g.: gravitationally induced?]

Mechanics as a ‘bus’ for connecting hybrid components: superconducting qubits, spins, photons, cold atoms, ....

Precision measurements
small displacements, masses, forces, and accelerations

Optomechanical circuits & arrays
Exploit nonlinearities for classical and quantum information processing, storage, and amplification; study collective dynamics in arrays
Converting photons into phonons
Converting photons into phonons
“Linearized” Optomechanical Hamiltonian

\[ \hbar g_0 \hat{a}^\dagger \hat{a} (\hat{b} + \hat{b}^\dagger) \]

\[ \hat{a} = \alpha + \delta \hat{a} \]

\[ \hbar g_0 (\alpha \delta \hat{a}^\dagger + \alpha^* \delta \hat{a}) (\hat{b} + \hat{b}^\dagger) \]

“laser-enhanced optomechanical coupling”: \( g = g_0 \alpha \)

\[ g_0 \sim \text{Hz} - \text{MHz} \]

bare optomechanical coupling (geometry, etc.: fixed!)

\( \alpha \)
laser-driven cavity amplitude tuneable! phase!
Cavity Optomechanics

Optomechanical Arrays

Topological Phases of Sound (and Light)

Dynamical Gauge Fields for the photons
Single-mode optomechanics

✓ displacement sensing
✓ cooling
✓ strong coupling
✓ self-oscillations (limit cycles)
Many modes

optical mode

mechanical mode
First realizations

Lipson group, Cornell arXiv:1505.02009 (synchronization)
Optomechanical crystals

= free-standing photonic crystal structures (Painter group)

advantages:

- tight vibrational confinement: high frequencies, small mass (stronger quantum effects)
- tight optical confinement: large optomechanical coupling (100 GHz/nm)
- integrated on a chip

Safavi-Naeini et al PRL 2014
Eichenfield et al Nature 2009
Optomechanical arrays

Optomechanical array: Many coupled optomechanical cells

Possible design based on “snowflake” 2D optomechanical crystal (Painter group), here: with suitable defects forming a superlattice (array of cells)
Modeling an optomechanical array

Tight-binding model for photons & phonons hopping and interacting on a lattice

\[ \Delta = \omega_L - \omega_{opt} \]

\[ \hat{H}_{om,j} = -\Delta \hat{a}_j \hat{a}_j + \Omega \hat{b}_j \hat{b}_j - g_0 (\hat{b}_j + \hat{b}_j^\dagger) \hat{a}_j \hat{a}_j + \alpha_L (\hat{a}_j^\dagger + \hat{a}_j) \]

\[ \hat{H}_{int} = -J \sum_{\langle i,j \rangle} (\hat{a}_i^\dagger \hat{a}_j + \hat{a}_i \hat{a}_j^\dagger) - K \sum_{\langle i,j \rangle} (\hat{b}_i^\dagger \hat{b}_j + \hat{b}_i \hat{b}_j^\dagger) \]

Max Ludwig, FM, Phys. Rev. Lett. 111, 073602 (2013)
Optomechanical Arrays

global view:
light-tunable metamaterial for photons & phonons

conceptually simple: one material, with holes

similar in spirit:
optical lattices
nonlinear optical materials
Cavity Optomechanics

Optomechanical Arrays

Topological Phases of Sound (and Light)

Dynamical Gauge Fields for the photons
Topological properties: robust against smooth changes!

- Möbius strip
- Knots
- Superfluid vortex
- n-fold torus

Images: Wikipedia
Waves can show topological robustness!
review: Hasan, Kane RMP 2010

Quantum Hall Effect (Chern number = conductance)

Topological Insulators:
- 2D topological insulators, e.g. HgTe
- 3D topological insulators, e.g. BiSe

Other than electronic systems?

Proposals/first experiments for:
- atoms, ions, photons, magnons

- cold atoms experiment: G. Jotzu et al. (Esslinger group), Nature 2014
- photons: Khanikaev, ... , Shvets, Nature Materials 2012
- Rechtsman, ..., Szameit Nature 2013
- Mittal, ..., Hafezi PRL 2014

- magnons: Zhang et al. 2013, Shindou et al 2013, Romhanyi et al 2015, ...
Chern number = \( \frac{\text{(sum of Berry phases across Brillouin zone)}}{2\pi} \)

\[ \text{Chern number} = \int \frac{1}{2\pi} dk_x dk_y \vec{\nabla} \times \langle \Psi_k | \vec{\nabla} | \Psi_k \rangle \]

Chern number = integer! topologically robust!
Edge States

Chern=0

‘trivial’ band insulator

Chern=1

topologically nontrivial band insulator

Chiral Edge State
Edge States

Chern=0

‘trivial’ band insulator

Chern=1
topologically nontrivial band insulator

Chiral Edge State
What about topological transport of phonons?

Engineer non-reciprocal phases for phonon transport!
What about topological transport of phonons?

Need:

- Dielectric (with the right pattern of holes)
- One Laser (with the right pattern of phases)
Gauge fields for phonons

(works best for phonons, due to $K \ll J$)

first such scheme: “phonon circulator”, Habraken, Stannigel, Lukin, Zoller, and Rabl, New Journal of Physics, 14, 115004 (2012)
Kagome Optomechanical Array

- optical defect mode
- mechanical defect mode

laser-field with different phases on sites A, B, C

defect

$\Phi$  $2\Phi$  $\Phi$

see Koch, Houck, LeHur, Girvin PRA 2010 for Kagome lattice in circuit QED
Creating an optical phase pattern
Topological Phases of Sound and Light in an Optomechanical Array

Vittorio Peano, Christian Brendel, Michael Schmidt, and Florian Marquardt, PRX 2015

a “weak coupling”: light field modifies phonon hopping
b “strong coupling”: photon and phonon bands mix
Topological Phases of Sound and Light in an Optomechanical Array

Topological Phase Diagram

laser frequency \(-(\Delta + \Omega)/J\)

laser amplitude \(g/K\)

weak coupling regime

increasing phonon hopping range

\[K = 10^{-3}J\]
Robust chiral transport of phonons

(a) light

local density of states

photon transmission probability

Probe beam

Kρ(ω) 2.8

(b) sound

local density of states

phonon transmission probability

Kρ(ω) 520
Robust chiral transport of phonons

Challenges (for optomechanical crystals)

fabrication disorder: current 1%
– need to reduce by factor 100 (postprocessing)
intensity requirement: ca. $10^5$-$10^6$ circulating photons
– OK, but large (optimize, improve coupling $g_0$)
• Topologically protected transport of phonons in the solid state

compare... coupled pendula
Süssstrunk, Huber Science ’15

coupled gyroscopes
Nash,...,Irvine, arXiv:1504.03362

• Here: nanostructure, tuneable
• Full optical control and readout
• Arbitrary domains
- study one-way phonon transport
- Time-dependent control: quenches, dynamical reconfiguration of edge states
- Photon/phonon polariton transport
- Classical nonlinear dynamics
- Thermalization in chiral edge states
- Quantum nonlinear dynamics: for larger $g_0$
Optomechanical Arrays

Cavity Optomechanics

Topological Phases of Sound (and Light)

Dynamical Gauge Fields for the photons
Synthetic magnetic fields

neutral atoms

cold atom realizations:
Aidelsburger et al (Bloch group) 2013,
Miyake et al (Ketterle group) 2013

photons

proposals:
Umucalilar and Carusotto, PRA 2011
circularly refractive medium
Hafezi, Demler, Lukin, Taylor, Nature
Physics 2011
tuneable: Fang, Yu, Fan Nature
Photonics 2012; proposed electrical
modulation of refractive index

Mittal, .... , Hafezi PRL 2014
coupled ring resonators
Artificial magnetic fields for photons

Need:

Dielectric
(with the right pattern of holes)

Two Lasers
(with the right pattern of phases)
Phonon-assisted photon tunneling

Mode 1 \hspace{1cm} \text{link} \hspace{1cm} \text{mode 2}

Mechanical vibration leads to modulation of effective photon tunnel coupling between mode 1 and 2

\[ \omega = \omega_2 - \omega_1 \]

\[ 2 \cos(\omega t + \phi)(\hat{a}_1^\dagger \hat{a}_2 + \hat{a}_2^\dagger \hat{a}_1) \approx e^{i(\omega t + \phi)} \hat{a}_1^\dagger \hat{a}_2 + e^{-i(\omega t + \phi)} \hat{a}_2^\dagger \hat{a}_1 \]

Non-reciprocal phase!

(similar to Fan group proposal, but mechanical vibration instead of electrical modulation)
Artificial magnetic fields for photons

arbitrary optical re-configuration of magnetic field distribution

Hofstadter butterfly spectrum

M. Schmidt, S. Keßler, V. Peano, O. Painter, F. Marquardt
Optica 2015
Optomechanical Hamiltonian:

phonon-assisted photon hopping

\[ H = \sum_j \nu_j a_j^\dagger a_j + \sum_l \omega_l b_l^\dagger b_l + \sum_{i,j} J_{i,j} b_{i,j}^\dagger a_j a_i + \text{H.c.} \]

Mechanical oscillation: now self-oscillations (pumped by blue-detuned laser), instead of externally driven

\[ x(t) \]

Amplitude B

S. Walter and FM, in preparation
amplitude and phase:
\[ a_j = A_j e^{i\theta_j} \quad b_{ij} = B e^{i\phi_{ij}} \]
gauge-invariant flux (seen by the photons)
\[ \Phi = \phi_{13} + \phi_{21} + \phi_{32} \]

Classical nonlinear dynamics:

mechanical phase dynamics
\[ \dot{\phi}_{ij} = -\omega_{ij} - \frac{J_{ij}}{B_{ij}} A_i A_j \cos(\phi_{ij} + \theta_{ij}) \]

optical phase dynamics
\[ \dot{\theta}_i = -\nu_i - \sum_{j \neq i} J_{ij} B_{ij} \frac{A_j}{A_i} \cos(\phi_{ij} + \theta_{ij}) \]

gauge transformation
\[ \phi'_{ij} = \phi_{ij} + (\chi_j - \chi_i) \]
\[ \theta'_i = \theta_i + \chi_i \]
Flux dynamics (3-site model)

**Adiabatic regime:**
- Fixed point $\neq \pi/2$
- Fixed point $\pi/2$

**Stages:**
- III periodic
- IV chaotic
Lattice: Photon flow reshapes flux

S. Walter and FM, in preparation
Optomechanical Arrays: Future possibilities

- Synthetic magnetic fields for photons/phonons
- Dirac Physics and other band structures
- Synchronization and Pattern Formation
- Quantum Information Processing
- Topological Phases
- Transport (edge states/wires)
- Nonequilibrium dynamics/Quench physics/Thermalization
- Strongly Correlated Quantum Physics?
- All-optical control/readout

“Topological Phases of Sound and Light”, Vittorio Peano, Christian Brendel, Michael Schmidt, and FM, Phys. Rev. X 5, 031011 (2015)
“Optomechanical creation of magnetic fields for photons on a lattice”, M. Schmidt, S. Keßler, V. Peano, O. Painter, FM Optica 2, 635 (2015)

more: see Oskar Painter’s talk this afternoon!