Possibility of Axion Dark Matter Search with Microresonators and Chiral Mirrors

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Department of Physics, University of Tokyo

Contents

- Introduction
- Microresonator **Long**
- Symmetry breaking **Long**
- Chiral mirror **Short**

Contents

- Introduction
- Microresonator
- Symmetry breaking
- Chiral mirror

References

- Microresonator
  - K. Vahala, Nature 424, 839–846 (2003)
- Symmetry breaking
  - L. Del Bino+, Scientific Report 7, 43142 (2017)
- Chiral mirror
  - A. Lakhtakia & J. Xu, Microwave and Optical Technology Letters 47, 1 (2005)
  - I. J. Hodgkinson+, Optics Communications 210, 201-211 (2002)
  - J. Xu+, Optics Communications 264, 235-239 (2006)

Why did I choose this topic?

- On October 5, Yan Haochen gave me an email with the title of "Interest of the DANCE project"
  - My paper was published to PRD on October 10
  - He found from arXiv? (but published arXiv since March···)
  - He found PRD accepted list and jumped to arXiv?

- His research topic: microresonators
- He is curious whether microresonators can be applied for axion dark matter search
- He also found papers about chirality and thinks it can be applied (Both he and I are not experts···)

- We exchanged 15 e-mails in two months
- He sent me many references
- I wanted to spend time to reading them with the opportunity for my seminar

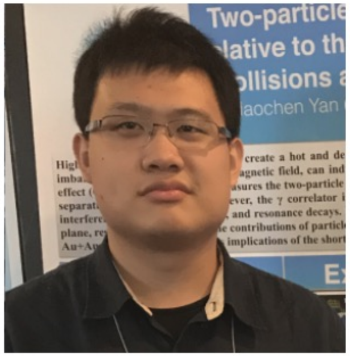
Profile of Haochen Yan

Haochen Yan

Haochen received his Bachelors in physics from University of California, Los Angeles, and Master's degree in Chemistry from University of Tokyo. He joined the group as a PhD student in 2021.

haochen.yan [at] mpl.mpg.de

Del'Haye Lab - People



- His first research topic is axion when he was an exchange student at UTokyo via UCEAP

ダークマター懇親会 - Slides

- His supervisor at Master course is Prof. Goda
  - Prof. Goda got his PhD at MIT LIGO group

Goda Lab

- Now he is a member of Del'Haye Lab (Microphotonics Research Lab), Max Planck Institute for the Science of Light

Contents

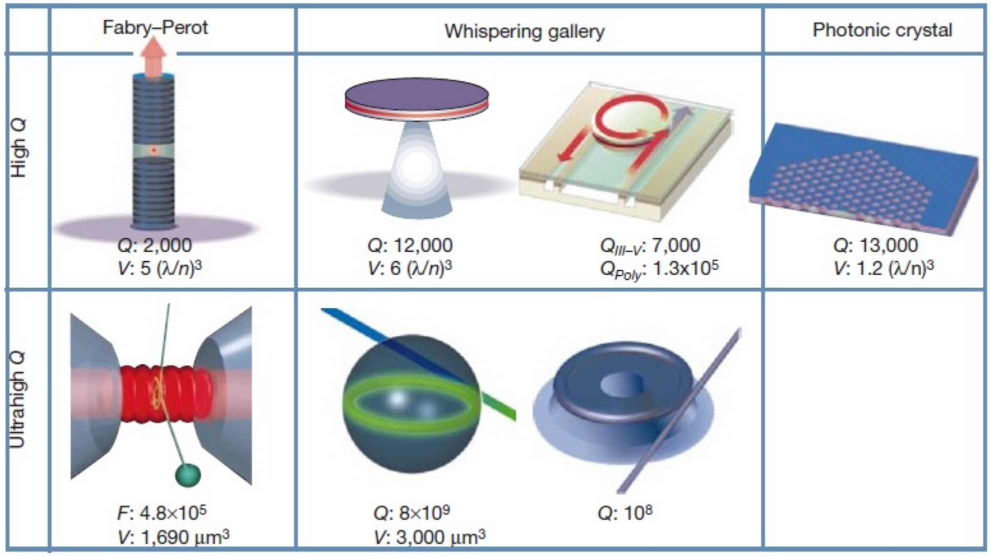
- Introduction
- Microresonator
  - Classification of microresonators
  - Whispering gallery resonator
  - Finesse and quality factor
  - Microresonators in Del'Haye Lab and DANCE
- Symmetry breaking
- Chiral mirror

Microresonators

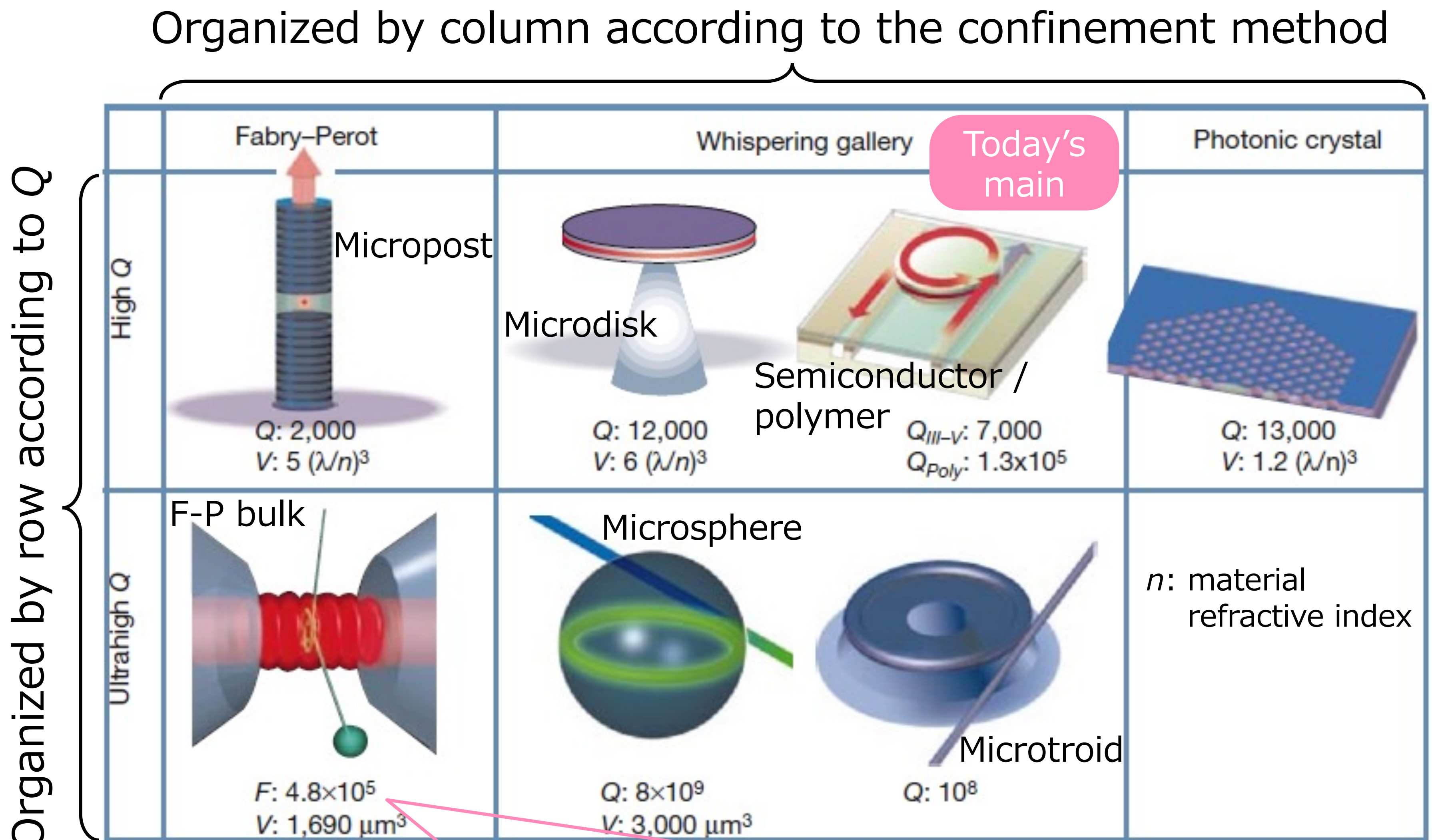
- Optical microresonators (or microcavities) confine light to small volumes by resonant recirculation

- An ideal cavity without loss would confine light indefinitely and would have resonant frequencies at precise values
- Deviation from this ideal condition is described by quality factor Q
- Q is proportional to the confinement time

- Q and microcavity volume V is important for applications of these devices



Classification of microresonators

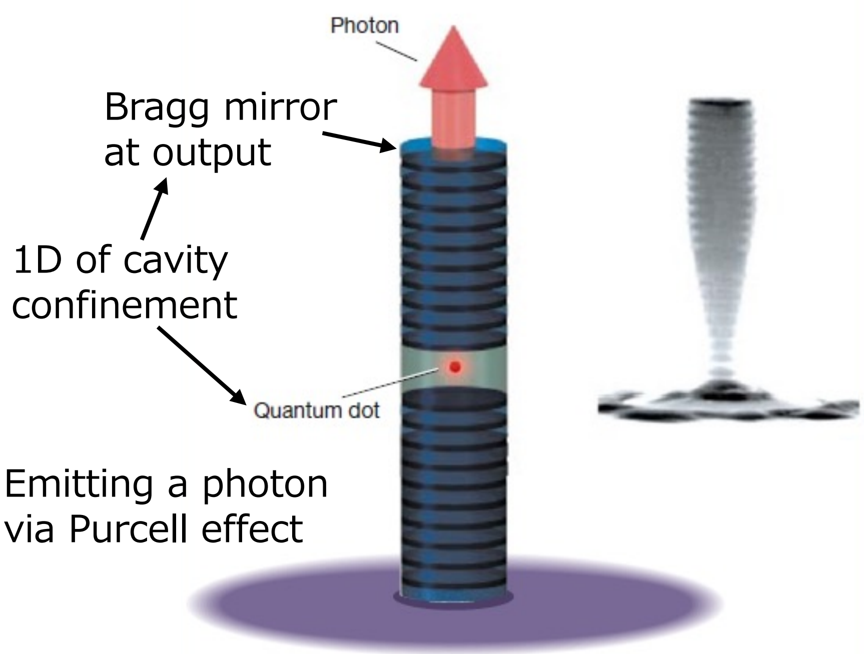


Finesse F is given for the ultrahigh-Q Fabry–Perot

- Equation between Q and F (later)

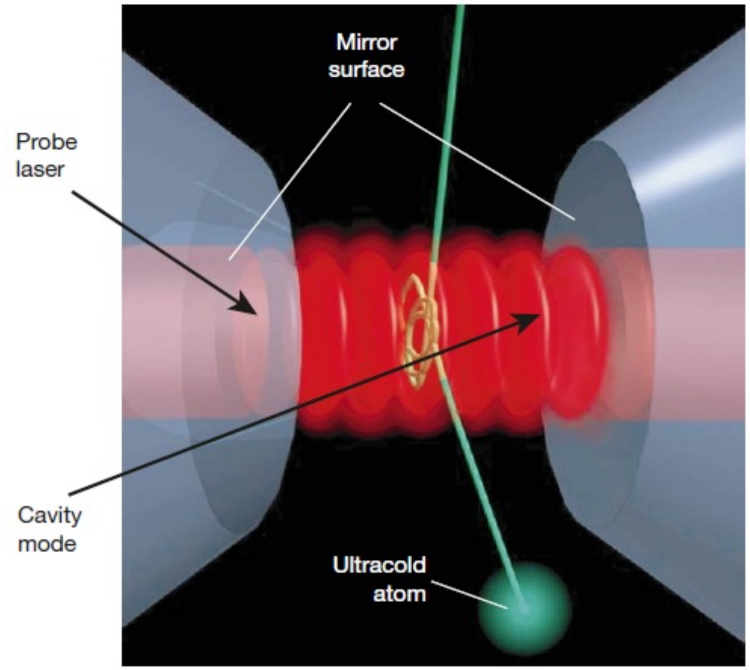
Fabry-Perot cavity

Micropost (or micropillar) cavity



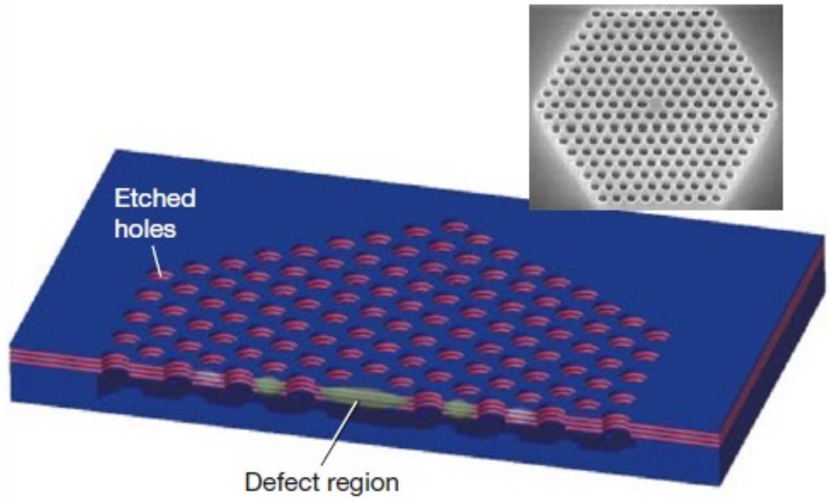
- A major role in applications of the Purcell effect to triggered, single-photon sources
- Small cavity volume and relatively high Q value
- Suitable for optical fibers

Fabry-Perot bulk optical cavity



- If the probe freq. is maintained at resonant freq., a single atom into the cavity block transmission
- Cavity is sensitive to atomic center-of-mass motion

Photonic crystal cavity

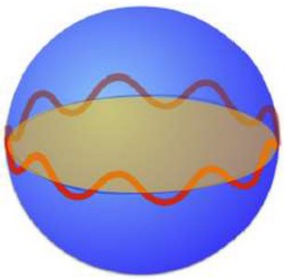


- Photonic crystal cavity can provide extremely small volumes
- Strong coupling is theoretically feasible; however, measured Q values are well below the theoretical optima at present

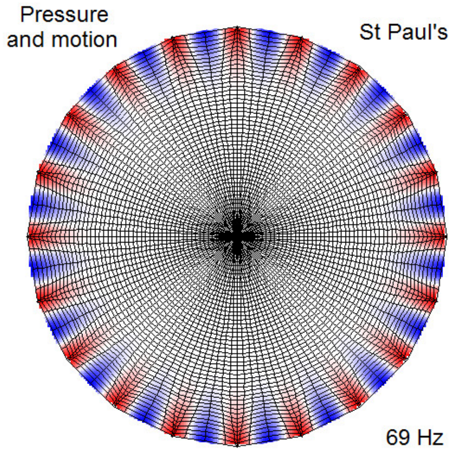
- Photonic crystal cavity is formed by dry etching a hexagonal array of holes
- One hole is left unetched creating a "defect"
  → Defect mode in the optical spectrum
- Defect mode is confined to the interior of the array by Bragg reflection in the plane and conventional waveguiding in the vertical direction

Whispering gallery mode resonance

- Whispering gallery mode resonance
  - Optical resonance phenomenon that occurs inside the sphere
  - $2\pi R = m\lambda$ m: (azimuthal) mode number



- Cf.) An acoustic whispering-gallery mode at 69 Hz in St Paul's Cathedral with the diameter of 33.7 m



G. Schunk+, Opt. Express 22, 30795 (2014)
JSPE - 講演概要集

Whispering gallery mode resonance

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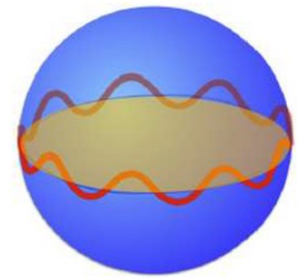
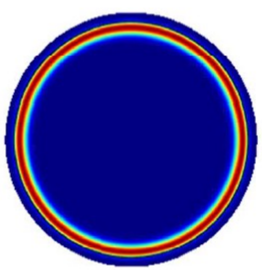


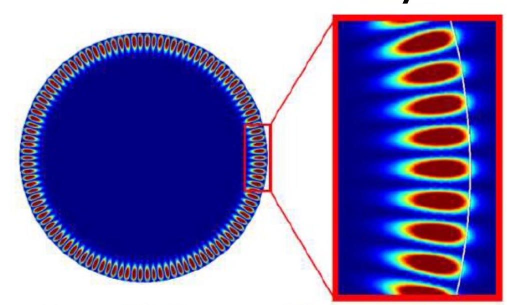
- Whispering gallery mode resonance has two states
  - Propagating light

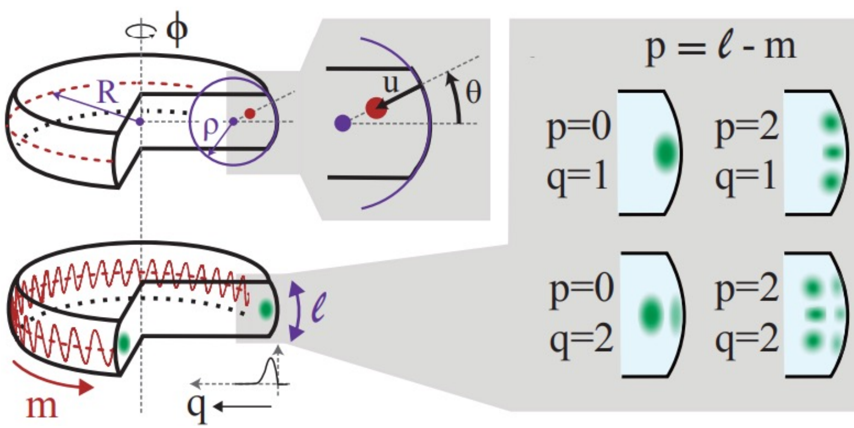


Light is propagating inside sphere at high speed
→ Result in a uniform intensity distribution

  - Standing wave

Static and periodic intensity distribution





l: polar mode number
m: azimuthal mode number
q: radial mode number

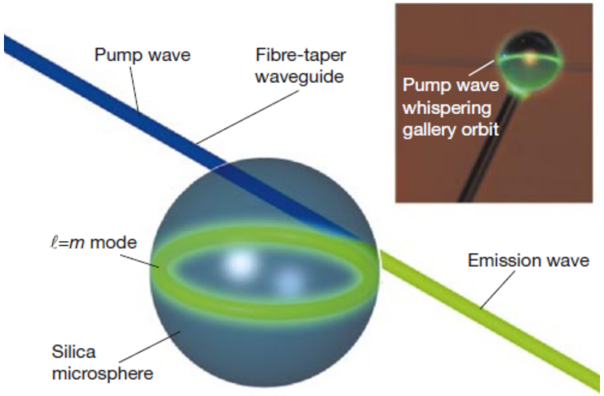
When *p* = *l*-*m* = 0,
l=*m* modes or
equatorial WGMs

G. Schunk+, Opt. Express 22, 30795 (2014)
JSPE - 講演概要集

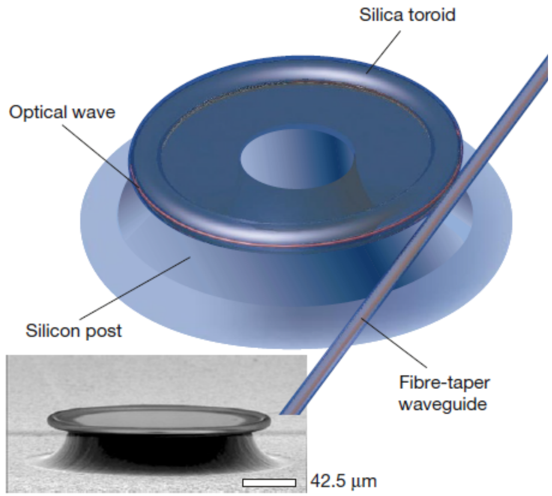
Whispering gallery resonator

- Whispering gallery resonators are usually made of silica and quartz microspheres
- Excellent surface finish is crucial for maximizing Q
  - The formation of spheres through surface tension provides smooth surface with only a few nm roughness
    $\rightarrow Q \sim 10^9$ or $F \sim 10^6$
  - Dependence of Q on sphere diameter is consistent with Q being limited by losses of surface roughness
  - A time dependence of measured Q is believed to result from water adsorption at the sphere's surface

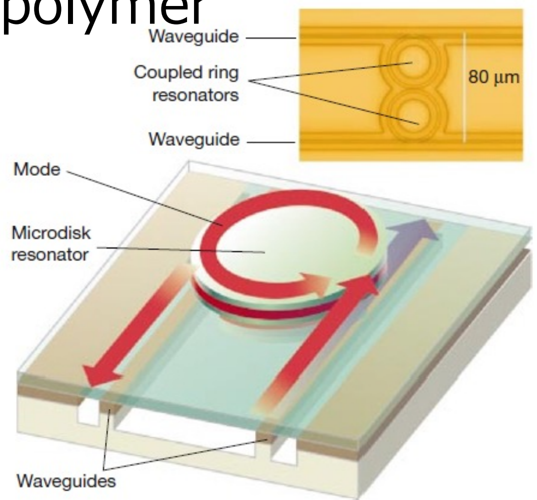
Microsphere



Microtroid



Semiconductor / polymer



Finesse and quality factor

- Finesse F is defined as the ratio of the free spectral range and the full width at half maximum of a resonance

$$F = \frac{\mathrm{FSR}}{\mathrm{FWHM}} = \frac{\Delta\lambda}{2\delta\lambda}$$

- Quality factor Q is the sharpness of the transmission peak and defined as the ratio of the resonance wavelength to the full width at half maximum

$$Q = \frac{\mathrm{wavelength}}{\mathrm{FWHM}} = \frac{\lambda}{2\delta\lambda}$$

- Relationship between Q and F

$$Q = \frac{n_{\mathrm{eff}} L_{\mathrm{cav}}}{\lambda} F$$

for a circular resonator with radius R and cavity length $L_{\mathrm{cav}} = 2\pi R$

Finesse and quality factor

Del'Haye Lab's microresonators

- I asked Yan about parameters of microresonators in Del'Haye Lab

- They use 1550 nm CW laser (Toptica) as pump laser
- Radius of microresonators: 50 μm - 100 μm

- Four main resonators
  - Rod type made of silica: $Q \sim 10^9$
  - Toroidal type made of silica: $Q \sim 10^6$
  - Ring type made of Si_3N_4: $Q \sim 10^6$ - 10^7
  - Ring type made of AlN: $Q \sim 10^5$

Comparison with DANCE

- Effective optical path length ($\sim F \times L$) of DANCE bow-tie cavity
  - DANCE Act-1: ~3 km
  - Final DANCE: $\sim 10^4$ km
- Effective optical path length ($\sim F \times L$) of microresonator in Del'Haye Lab
  - Microresonator: ~10 km

    ($Q \sim 10^9$, $\lambda = 1550$ nm, $R = 50$ μm, $n_{\mathrm{eff}} = 1.44 \rightarrow F = 3\times10^7$)

- Microresonator could be used for DANCE Act-1
- It is good that polarization flipping does not occur in the ring microresonators
- Seems difficult to use for final DANCE because the larger the sphere, the more surface loss and the more difficult it is to increase Q
- How much high power can microresonators withstand?
- How do they measure polarization rotation? (→ next topic)

Contents

Introduction of symmetry breaking

- Symmetry breaking:
  interesting phenomenon in whispering gallery resonators
- Research topic by Dr. Lewis Hill, sensior scientist at Del'Haye Lab
- Yan and Lewis are discussing the method of detecting polarization rotation via the symmetry breaking
- Yan said they started detailed theoretical calculation on the symmetry and it might enhance the sensing ability

- I still don't understand it very much, so I asked some questions to Yan on this Monday
- Yan forwarded my email to Lewis
- We will be discussing this topic later

Kerr effect

- (Electro-optical) Kerr effect: a phenomenon in which the refractive index changes in proportion to the square of the strength of the electric field when an electric field is applied to a certain material

$$\Delta n \propto n_2 \, |E|^2$$

  - Cf.) Pockels effect: $\Delta n \propto |E|$

  - Cf.) Magneto-optical Kerr effect: a phenomenon in which reflected light becomes elliptically polarized when linearly polarized light is reflected on the surface of a magnetized material
    - Cf.) Faraday effect: transmission rather than reflection

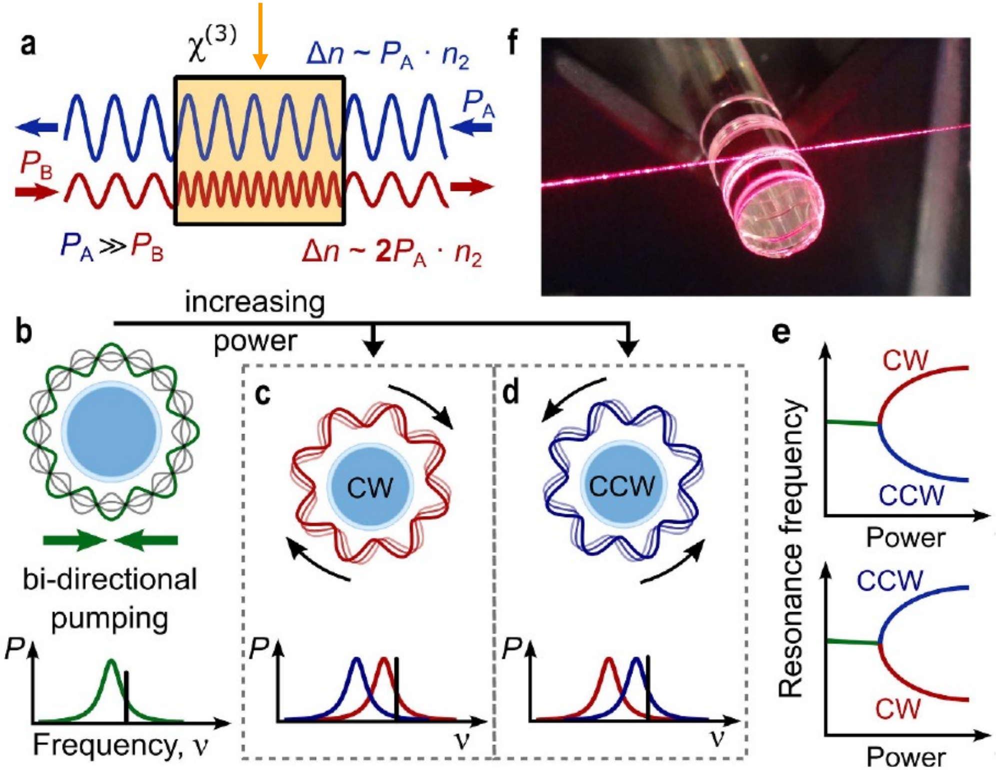
オプティペディア - Kerr効果

Principle of symmetry breaking (1)

- Two counter-propagating light waves have equal wavelength outside of a nonlinear Kerr medium

  ↔ Will have different wavelengths within the medium if their powers are unequal

Nonlinear Kerr medium



$$\Delta n_A = \frac{n_2}{A_{eff}}(P_A + 2P_B)$$

$$\Delta n_B = \frac{n_2}{A_{eff}}(P_B + 2P_A),$$

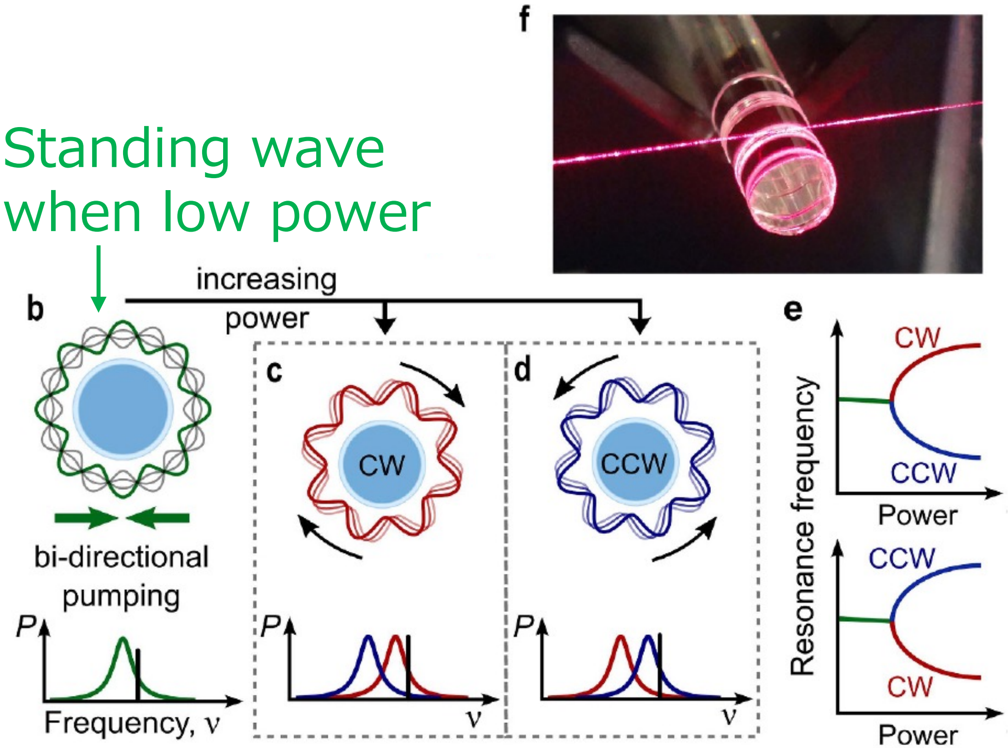
When $P_A \gg P_B$,
λ_A becomes longer
and λ_B becomes shorter
→ Splitting of resonant freq.

Principle of symmetry breaking (2)

- For low optical powers, the clockwise (CW) and counterclockwise (CCW) circulating powers remain equal
- Above a certain threshold power, however, the state with equal coupled powers becomes unstable, and the system instead chooses one of the two states

  = "Symmetry breaking"

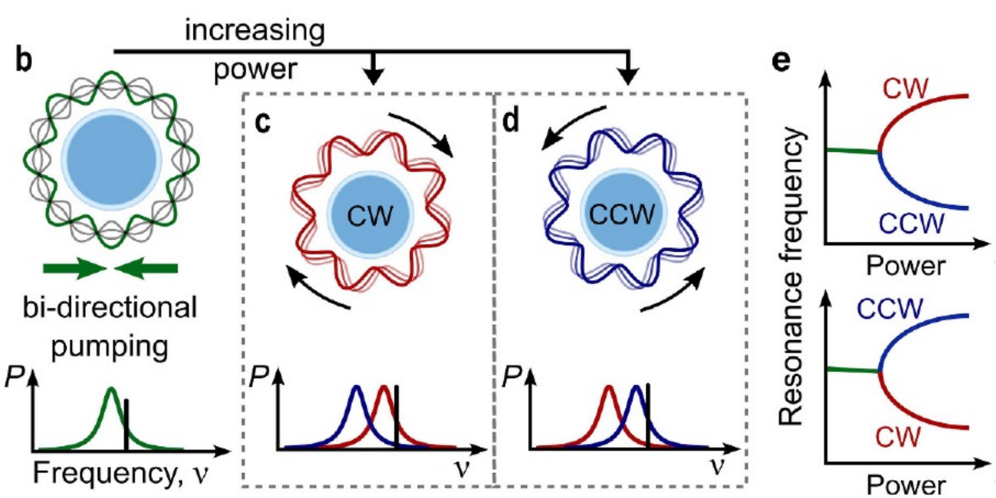
Standing wave when low power



$$P_{\text{thresh.}} = \frac{1.54}{\eta}\frac{\pi n_0^2 V}{n_2 \lambda Q Q_0}$$

Principle of symmetry breaking (3)

- Symmetry breaking might be explained by a self-amplification of small power fluctuations between two waves
- With the higher freq. compared to resonance, the optical mode with lower power experiences a stronger Kerr-shift and is pushed further away from pump laser freq.
- Simultaneously, the stronger mode experiences less Kerr-shift and moves towards pump laser
- This increases the resonance splitting until the system comes to a new equilibrium (self-phase modulation prevents the stronger mode from further approaching the laser)



$$P_{\mathrm{CW}} = \frac{\eta P_{\mathrm{in,CW}}}{1 + \left(\frac{\delta}{\gamma} + \frac{1}{P_0}(P_{\mathrm{CW}} + 2P_{\mathrm{CCW}})\right)^2}$$

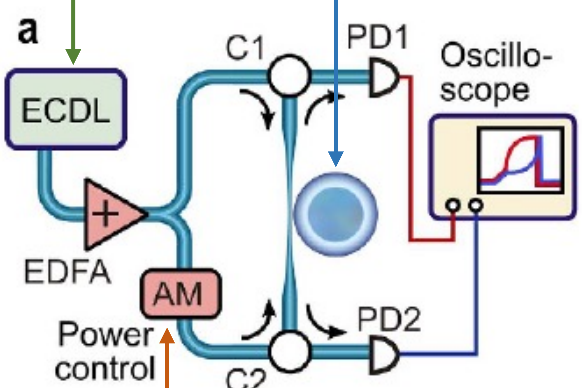
$$P_{\mathrm{CCW}} = \frac{\eta P_{\mathrm{in,\,CCW}}}{1 + \left(\frac{\delta}{\gamma} + \frac{1}{P_0}(P_{\mathrm{CCW}} + 2P_{\mathrm{CW}})\right)^2}$$

Here, $P_{\mathrm{in,\,CW}}$ and $P_{\mathrm{in,\,CCW}}$ are the incident pump powers, δ is the detuning of the laser frequency with respect to the resonance without Kerr shift, $\gamma = \gamma_0 + \kappa$ is the loaded half-linewidth of the resonance for intrinsic and coupling-related decay rates γ_0 and κ, and $\eta = 4\kappa\gamma_0/\gamma^2$ is the coupling efficiency.

Experiment of symmetry breaking

1550 nm

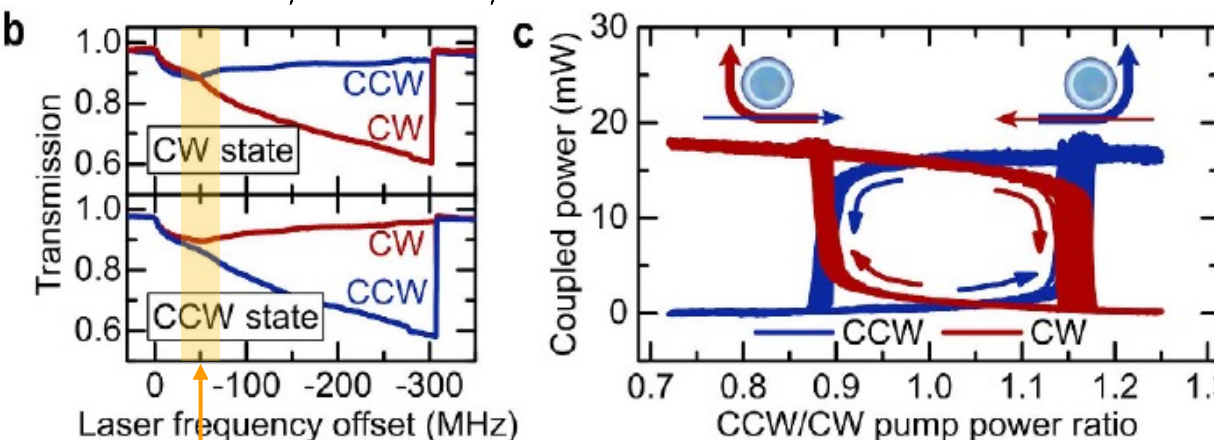
D = 2.7 mm
Q = 7×10[7]



Power ratio $P_{\text{in, CCW}}$ / $P_{\text{in, CW}}$ can be changed

Result: cavity scan with $P_{\text{in, CCW}} = P_{\text{in, CW}}$

Result: hysteresis

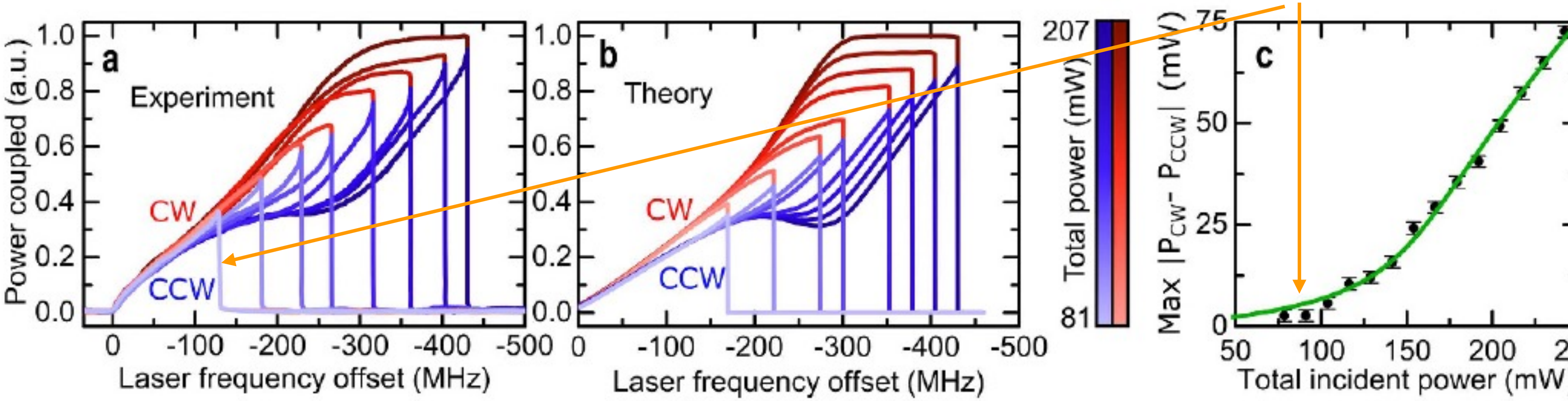


Symmetry breaking with P_{thresh} = 10 mW

Laser freq. = const.,
Modulate $P_{\text{in, CCW}}$ at 5 kHz by ± 25%

Result: cavity scan with $P_{\text{in, CCW}}$ / $P_{\text{in, CW}}$ = 0.9

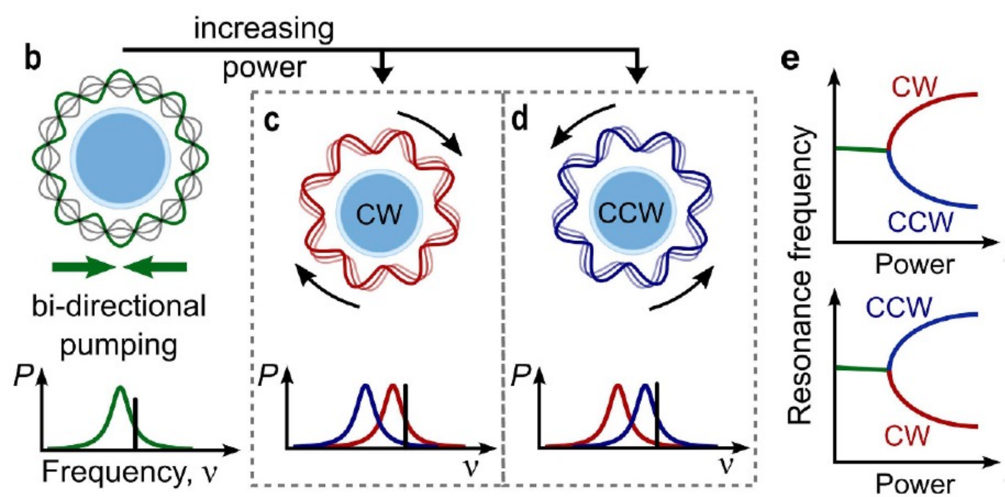
No breaking when low power



My question to Yan (1)

In the case of CW state, for example, the freq. of CW light is closer to the resonant freq. of pump laser than that of CCW light, but both CW and CCW light don't have the frequency same as pump laser and seems not to be resonant in microresonators.

For our DANCE project, it is important that both s- and p-polarization can be resonant in the cavity to enhance the sensitivity. I am wondering whether if this effect can be used for axion DM search.



My question to Yan

In [1], they consider two copropagating fields with left and right circular polarizations or two counterpropagating fields with equal linear polarization. In [2], they said symmetry breaking can be used as sensitive sensors. You also said that the detection of polarization rotation can be realized via symmetry breaking. Related to the previous question, I would like to ask in more detail how you will use this symmetry breaking in axion DM search.

[1] M. T. M. Woodley+, Phys. Rev. A 98, 053863 (2018)

[2] L. Hill+, Phys. Rev. A 101, 013823 (202)

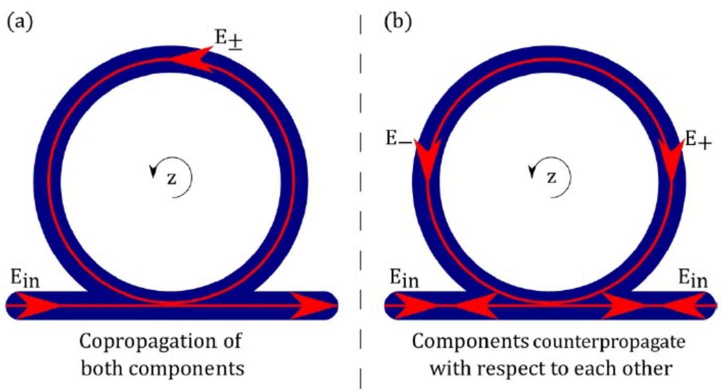


FIG. 1. Ring resonator setups, showing (a) copropagation of two light components with left and right circular polarizations and (b) the counterpropagation of two light beams, linearly polarized along the same axis.

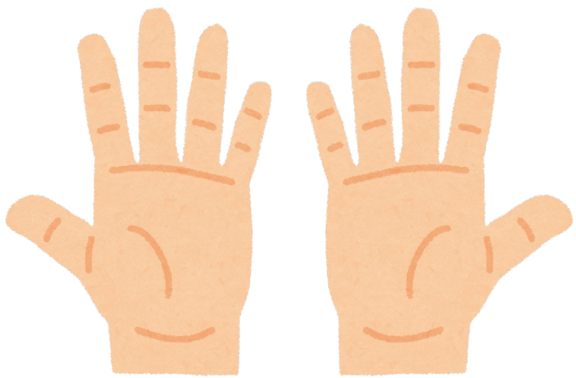
Contents

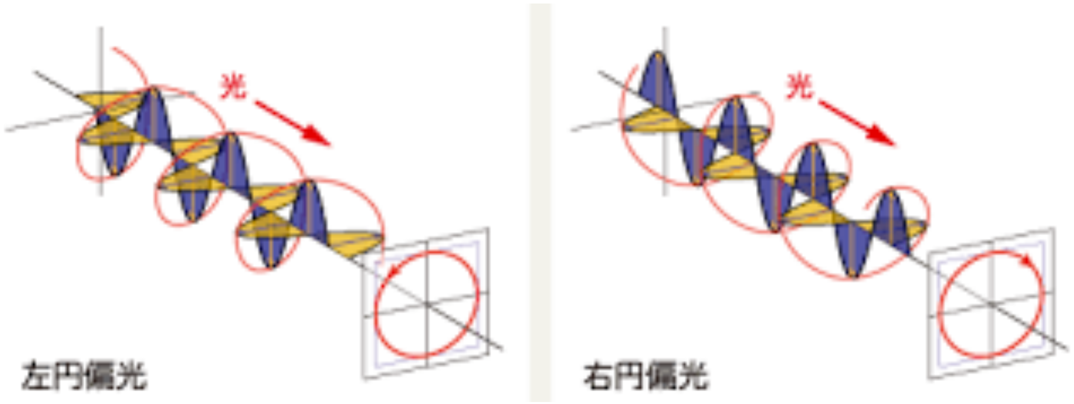
- Introduction
- Microresonator
- Symmetry breaking
- Chiral mirror
  - Dielectric mirror and chiral mirror
  - Cavity design with chiral mirror
  - Actual example of chiral mirror
  - Axion DM search with chiral mirror

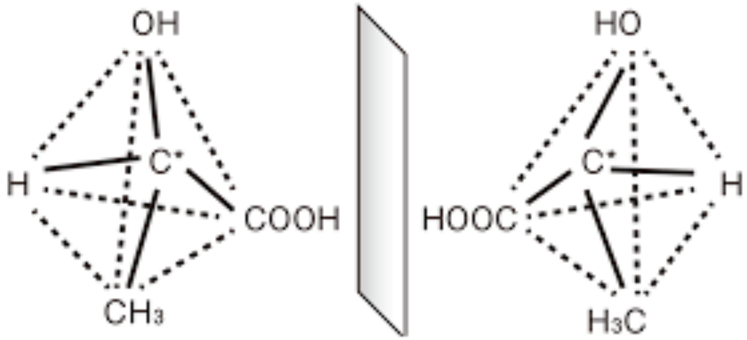
Introduction of chirality

- Chirality (カイラリティ or キラリティ):
  the property that a three-dimensional object cannot be superimposed on its mirror image

- Ex.) Hands, circular polarized light, mirror isomers

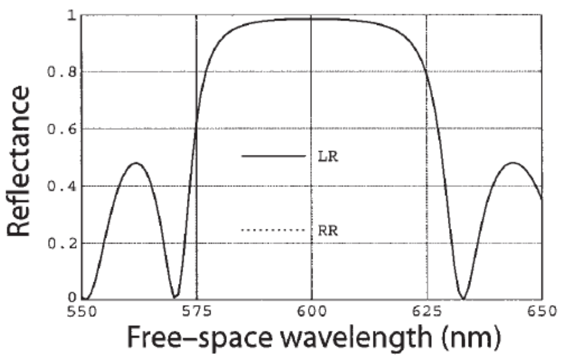






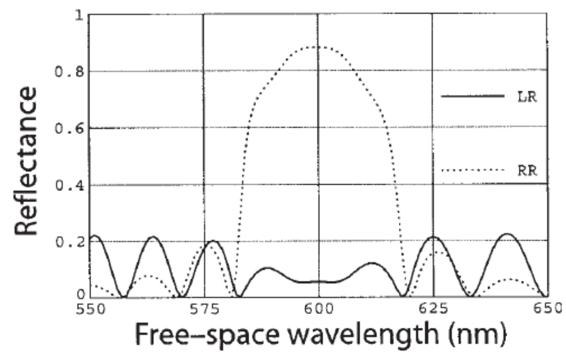
Dielectric mirror and chiral mirror

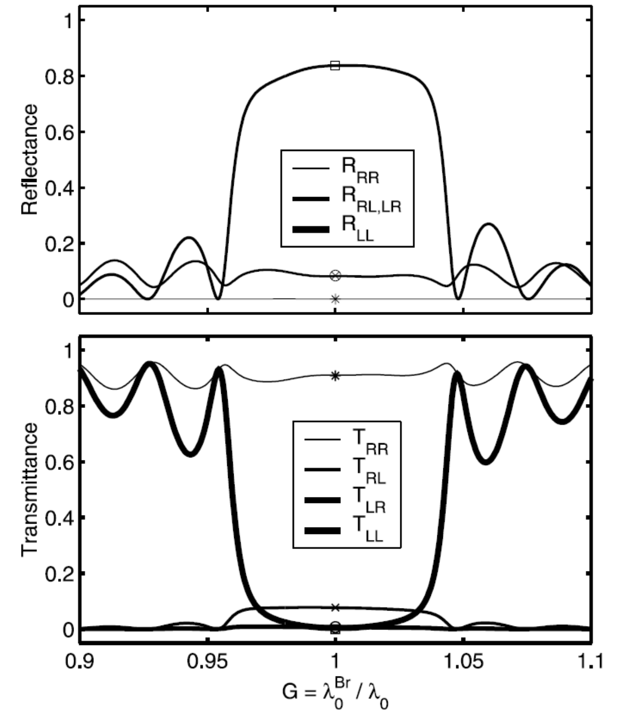
Nominal dielectric mirror



- Right circularly polarized light reflects as left circularly polarized light (R_{LR} = 100%, R_{RR} = 0%)

Chiral mirror



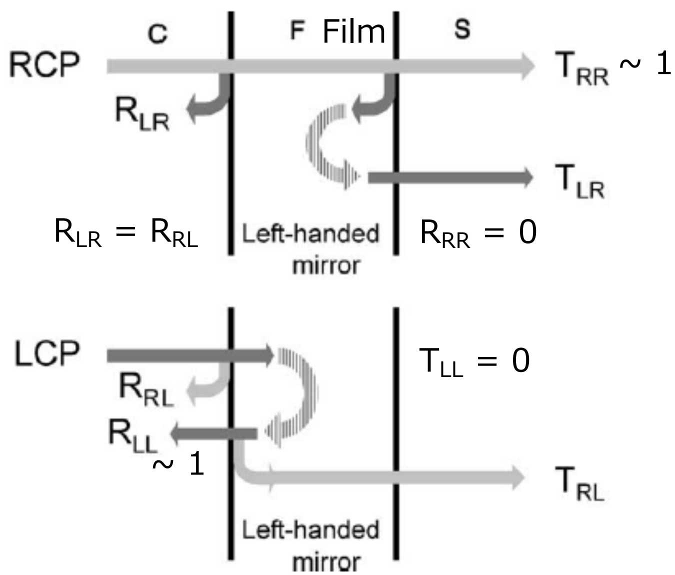


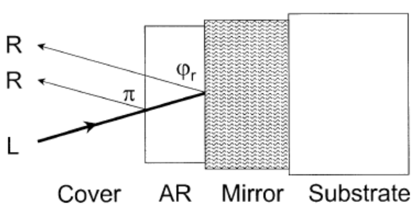
- Right circularly polarized light reflects as right circularly polarized light (R_{RR} ~ 100%, R_{LR} ~ 0%)
- Left circularly polarized light is transmitted

Cavity design with chiral mirror

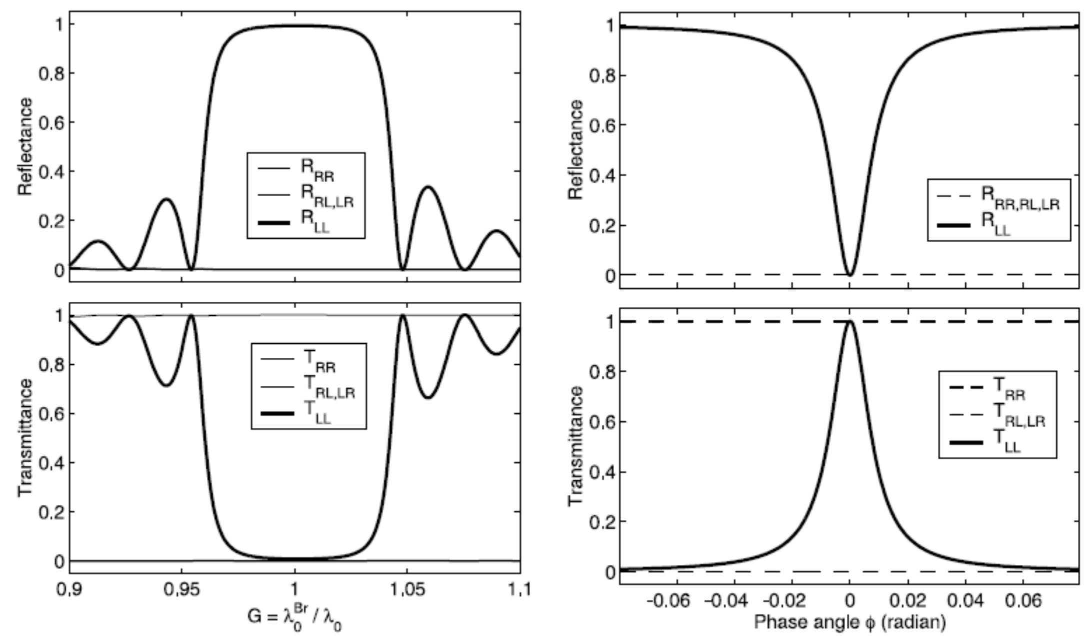
- Issue to build a cavity: low reflectivity of chiral mirror
  - R_{LL} = 82%, R_{RL} = R_{LR} = 9%
- Simulation results: R_{RL} is reduced from 9% to 0.03% by standard AR coatings, to 0.000003% by phase and amplitude matched AR coatings

Energy flow model of left-handed chiral reflector





Simulation results



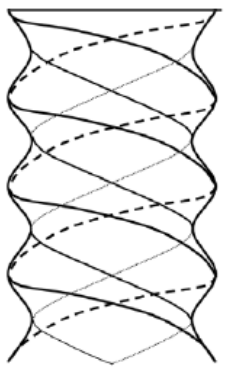
Actual example of chiral mirror

One actual example: a layer of fluorescent molecules (Alq3)

[wikipedia - トリス(8-キノリノラト)アルミニウム]

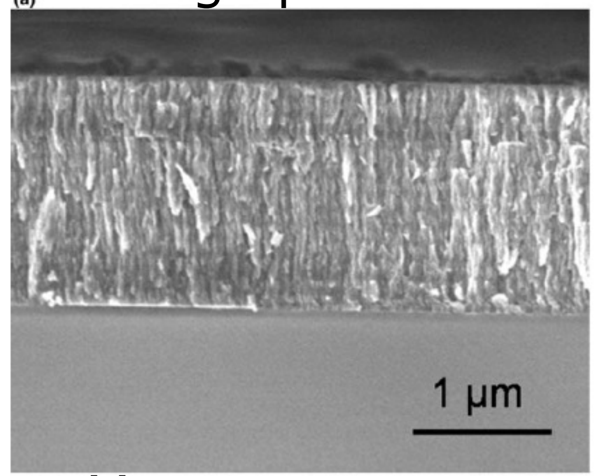
Screw-shape nanowire in left-handed chiral reflector

(a)

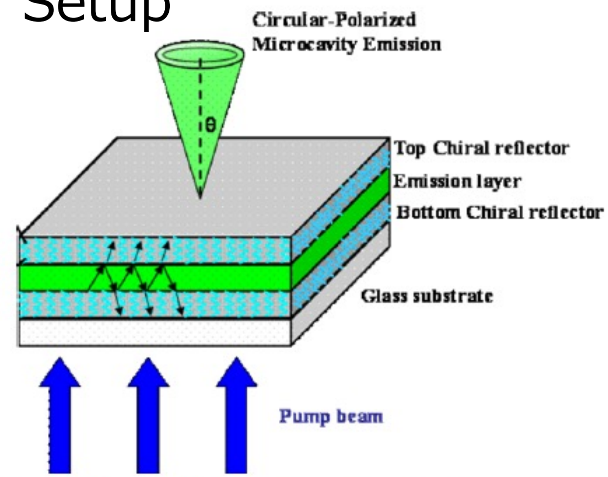


Scanning electron micrograph

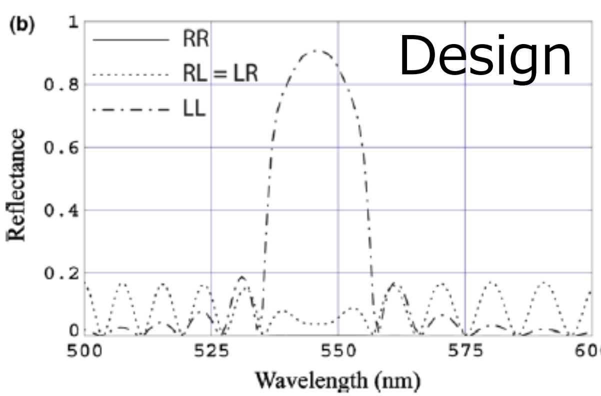
(a)



Setup

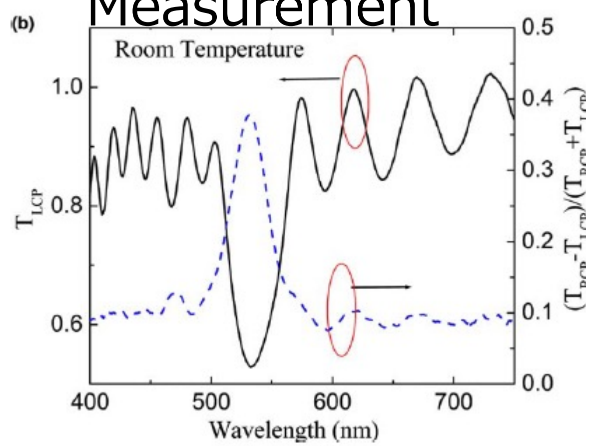


(b)



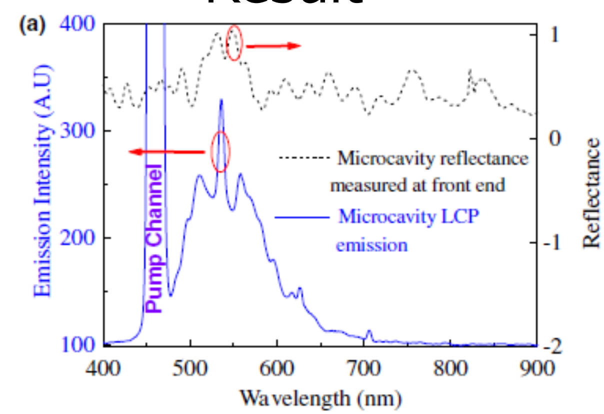
Measurement

(b)



Result

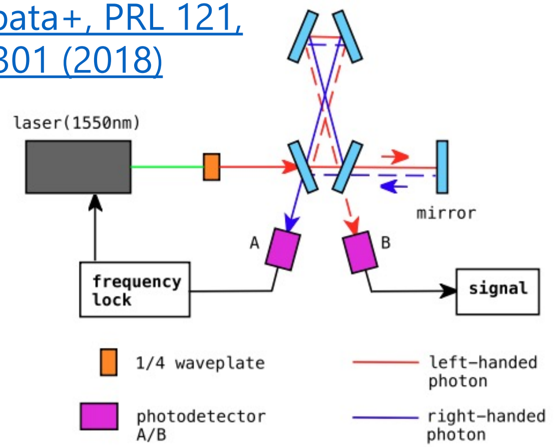
(a)



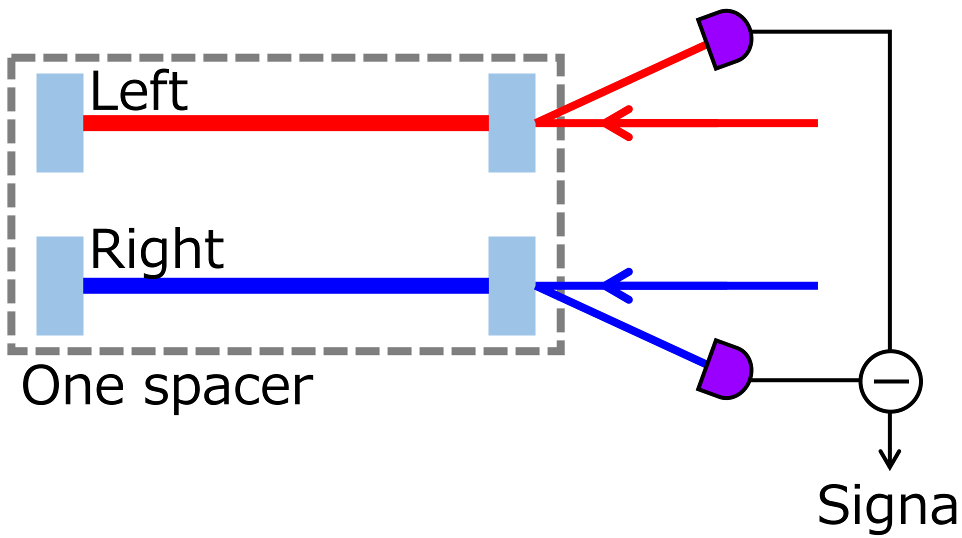
Axion DM search with chiral mirror

- Advantage: no need to make a bow-tie cavity
- Issue: no chiral mirror to affect both left- and right-circular polarized light
  → Need to make two linear cavities
  → No problem in principle, but common mode rejection ratio becomes small
  → Two holes for the cavities in one spacer as in Sugimoto-san's experiment at ISAS?

[I. Obata+, PRL 121, 161301 (2018)]



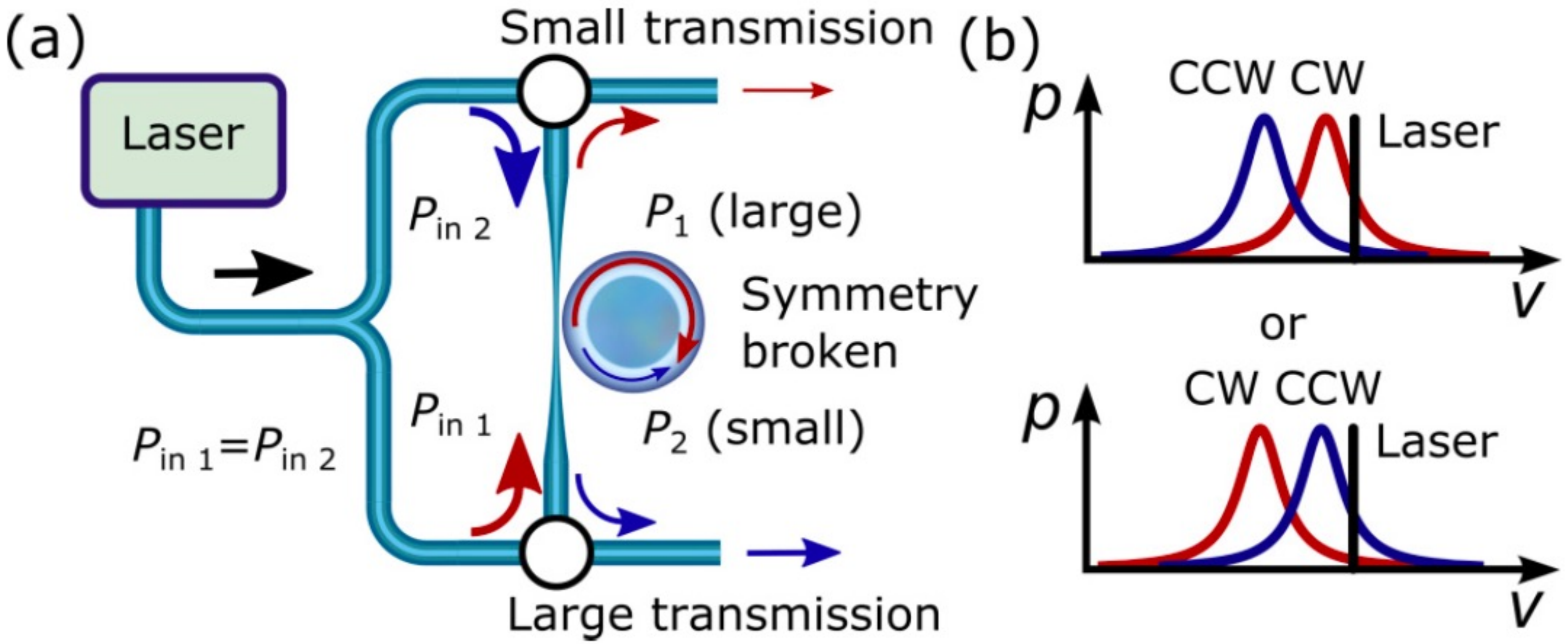
DANCE proposal:
right-circular polarized light,
double pass, null measurement



Summary

- Microresonators have relatively small size but high Q than our bow-tie cavity
  - Might be used for DANCE Act-1
- Yan and Lewis said symmetry breaking might be used to detect polarization rotation
  - Still a lot of questions
  - Need to be discuss with them
- Chiral mirror can reflect left (right) circularly polarized light as left (right) circularly polarized light
  - Good application to DANCE
  - High reflectivity was an issue
  - Need to consider cavity design

Extra slide



(a)
Laser
Small transmission
$P_{in\ 2}$
P_1 (large)
Symmetry
broken
$P_{in\ 1}$
$P_{in\ 1}$=$P_{in\ 2}$
P_2 (small)
Large transmission
(b)
p
CCW CW
Laser
ν
or
p
CW CCW
Laser
ν