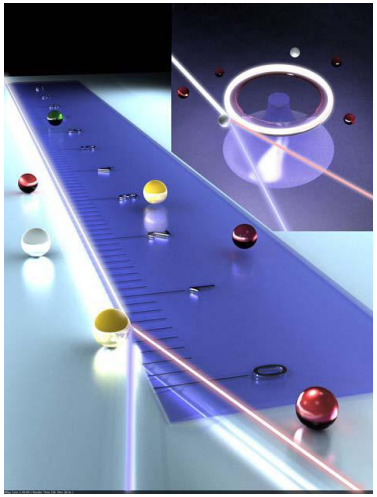
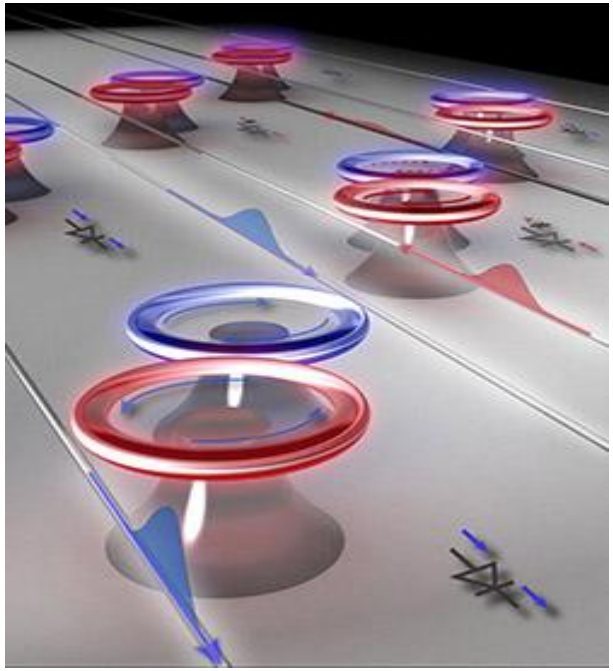
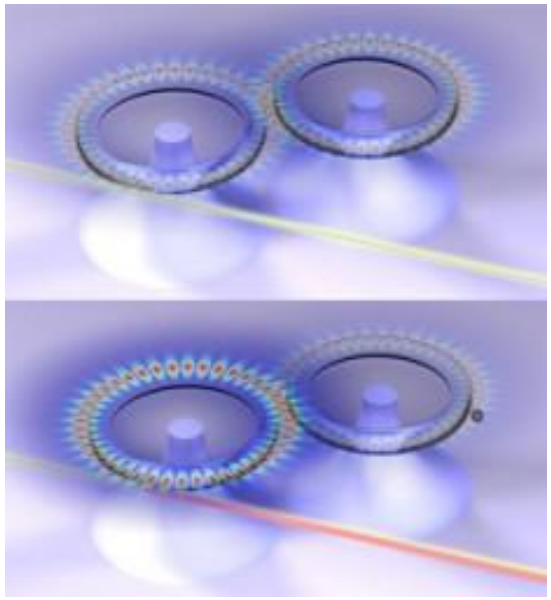
Controlling Light at Exceptional Points







Bo Peng

Sahin Kaya Ozdemir

Micro/Nano-Photonics Lab.
Electrical & Systems Engineering, Washington University, St. Louis, USA

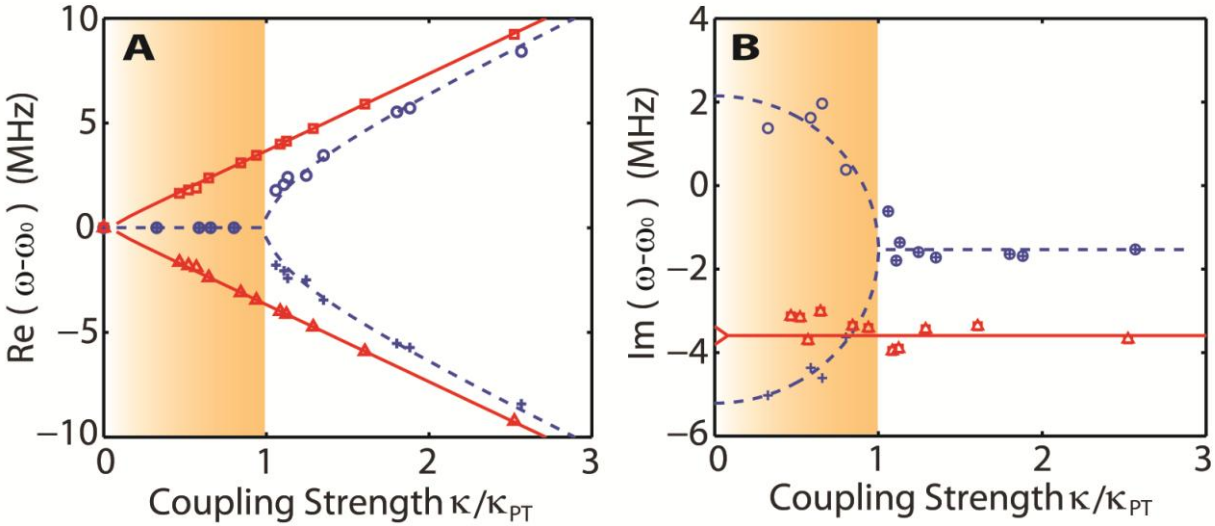
In collaboration with L. Yang and C. Bender (WashU), F. Nori (RIKEN), S. Fan (Stanford)
S. Rotter (TUV), and J. Wiersig (Magdeburg)

Agenda

1. PT and EP in optical systems: Brief review
2. Whispering-gallery-mode (WGM) resonators
3. PT-symmetric WGM microresonators
4. Loss-induced suppression and revival of lasing at an EP
5. Chiral modes and directional emission at EPs
6. Conclusions

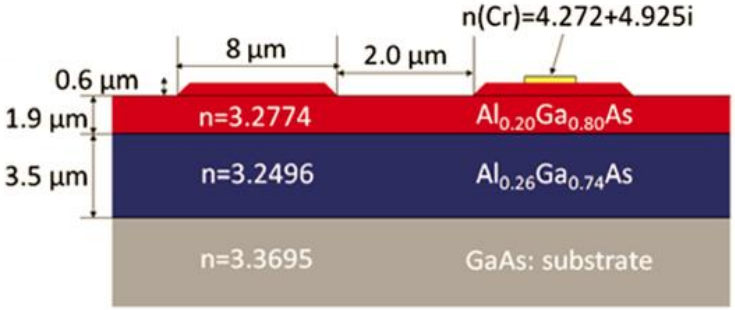
Exceptional point

- A non-Hermitian degeneracy where two (or more) eigenvalues and the corresponding eigenstates of a system coalesce
- Parity-time (PT) symmetry phase transition point in gain-loss balanced systems

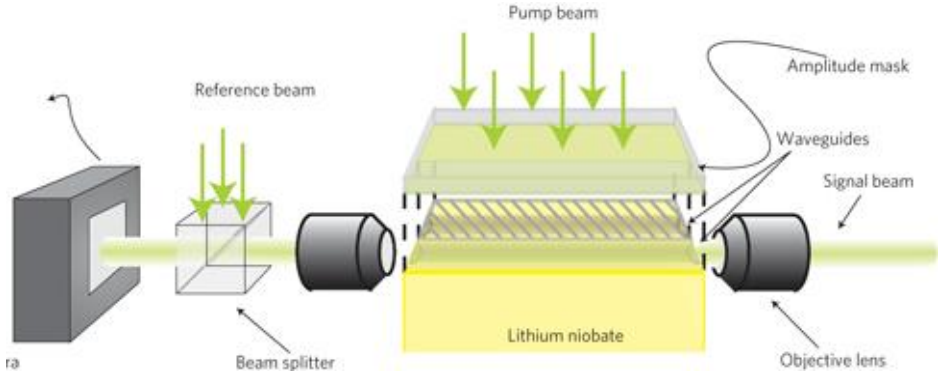


- Operating close to or at an EP leads to interesting phenomena

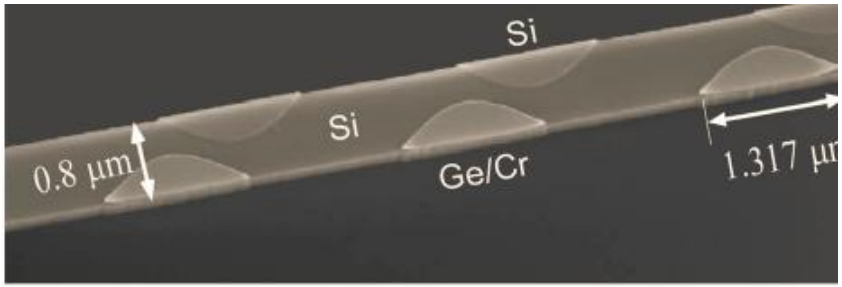
EP and PT in Optics-- Experiments



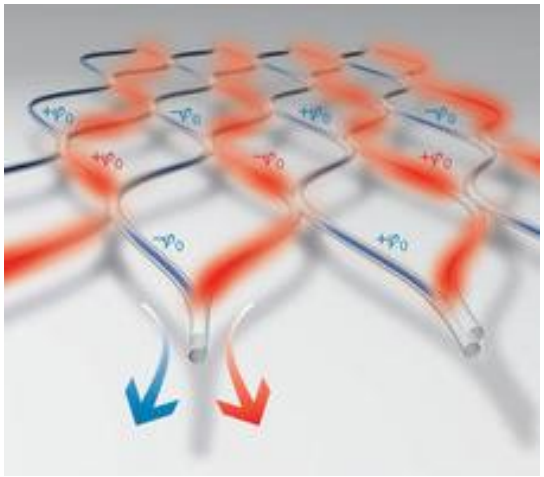
Loss-induced transparency in coupled passive waveguides. [Guo et al . PRL, 2009]



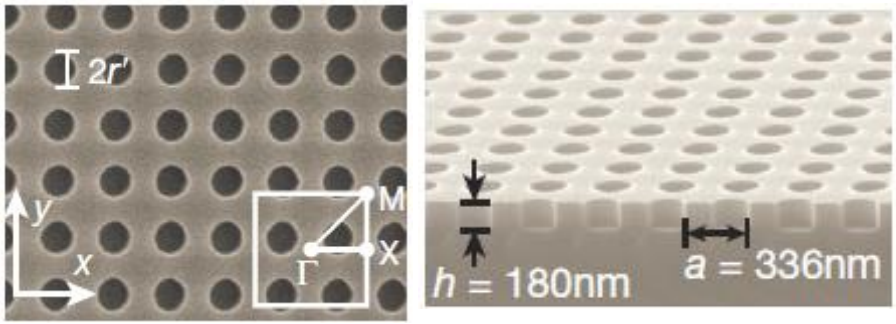
Asymmetric power oscillations in Coupled waveguides with balanced gain/loss. [Ruter et al. Nat. Phys, 2010]



Si waveguide with periodical modulatied permittivity. Unidirectional reflectionless propagation.[Feng et al . Nat. Mat. 2013]

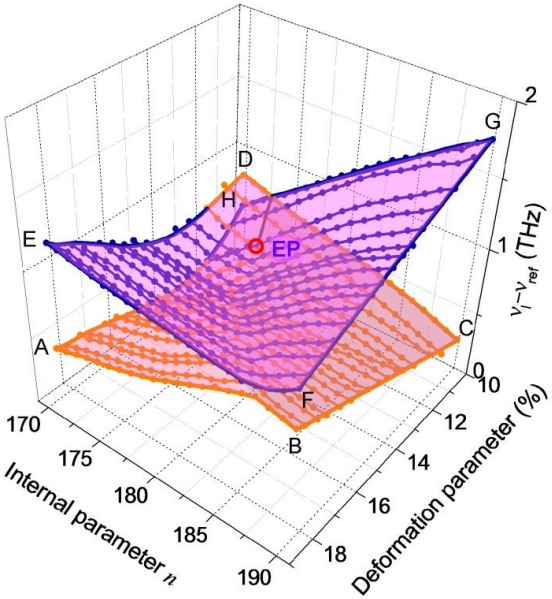


PT-symmetric temporal lattice by two coupled fibre loops periodically switching between gain and loss. [Regensburger et al .Nature 2012]

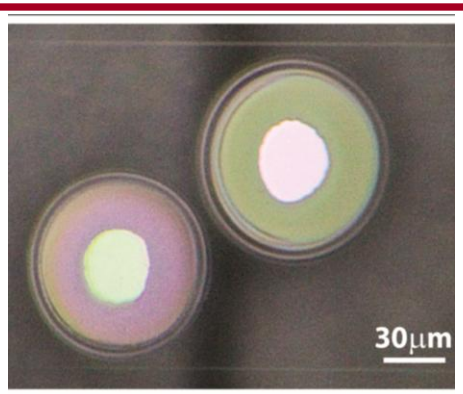


Rings of EPs in a 2D photonic crystal due to radiation losses [Chen et al. Nature 2015]

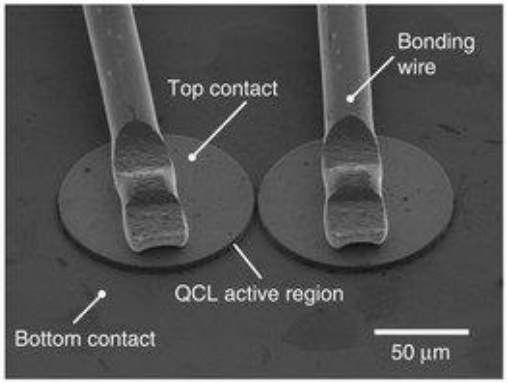
EP and PT in Optics-- Experiments



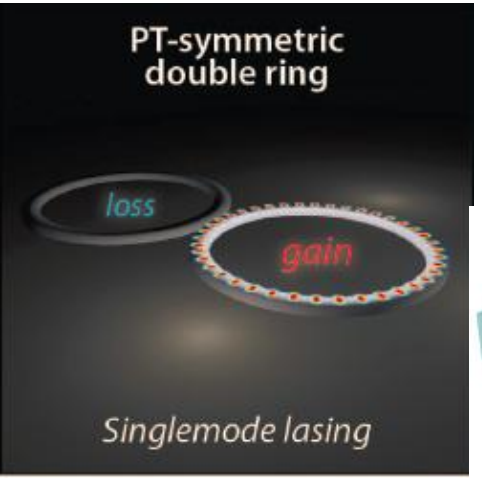
EP in a deformed cavity (liquid jet) [Lee et al . PRL, 2009]



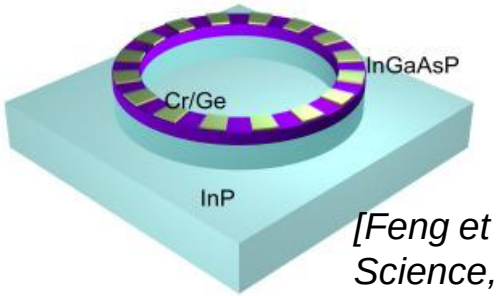
PT-symmetry and its breaking in WGM coupled microtoroids with balanced gain and loss [Peng et al . Nat. Phys, 2014]



Reversing the pump dependence of a laser at an EP [Brandstetter et al . Nat. Comm, 2014]

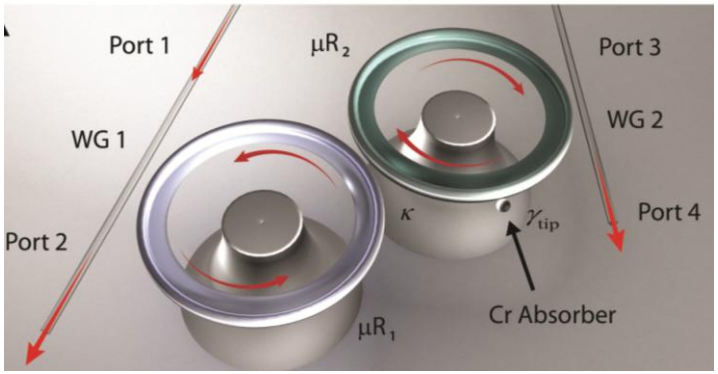


Single-mode lasing by PT-symmetry breaking [Hodaei et al . Science, 2014]



[Feng et al . Science, 2014]

Loss-induced suppression and revival of a Raman laser at an EP [Peng et al . Science, 2014]



Agenda

1. PT and EP in optical systems: Brief review
2. Whispering-gallery-mode (WGM) resonators
3. PT-symmetric WGM microresonators
4. Loss-induced suppression and revival of lasing at an EP
5. Chiral modes and directional emission at EPs
6. Conclusions

Whispering galleries

St. Paul Cathedral, London (1675)

Hagia Sophia, Istanbul (537)

Union Station, St. Louis(1890)

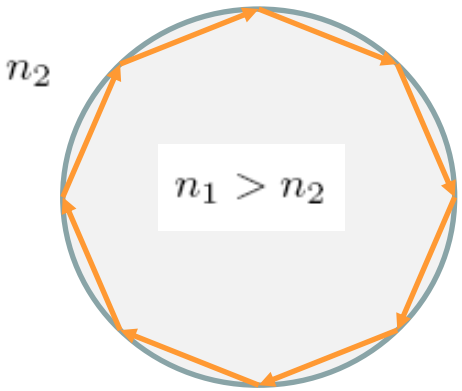
… sound waves are confined along the walls and propagate and refocused through internal reflections

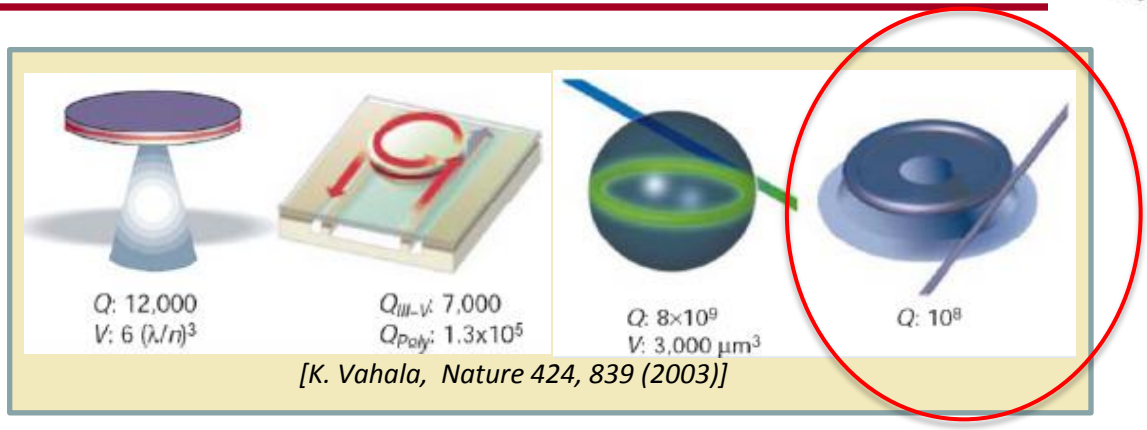
…explained by Lord Rayleigh for the first time

We are interested in structures which propagates light in the same way

Whispering Gallery Optical Resonators

Total internal reflection





[K. Vahala, Nature 424, 839 (2003)]

Low Optical Loss → Sharp Resonant → High-quality factor (Q) → Long photon lifetime

Micro-scale mode volume (V) → Tight Light Confinement → Intense Resonant Light

Long Photon Lifetime + Intense Light = Enhanced Light-Matter Interaction

Applications of WGM resonators

NATURE | VOL 415 | 7 FEBRUARY 2002 | www.nature.com

Ultralow-threshold Raman laser using a spherical dielectric microcavity

S. M. Spillane, T. J. Kippenberg & K. J. Vahala

nature photonics ARTICLES
PUBLISHED ONLINE: 2 NOVEMBER 2014 | DOI: 10.1038/NPHOTON.2014.253

Nonlinear π phase shift for single fibre-guided photons interacting with a single resonator-enhanced atom

Jürgen Volz*, Michael Scheucher, Christian Junge and Arno Rauschenbeutel*

nature nanotechnology ARTICLES
PUBLISHED ONLINE: 31 AUGUST 2014 | DOI: 10.1038/NNANO.2014.180

Single-molecule nucleic acid interactions monitored on a label-free microcavity biosensor platform

Martin D. Baaske, Matthew R. Foreman and Frank Vollmer*

nature physics ARTICLES
PUBLISHED ONLINE: 7 JUNE 2009 | DOI: 10.1038/NPHYS1304

Resolved-sideband cooling and position measurement of a micromechanical oscillator close to the Heisenberg uncertainty limit

A. Schliesser [1*], O. Arcizet [1*], R. Rivière [1*], G. Anetsberger [1] and T. J. Kippenberg [1,2†]

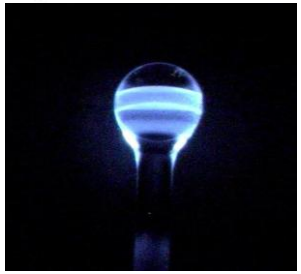
Optomechanically Induced Transparency

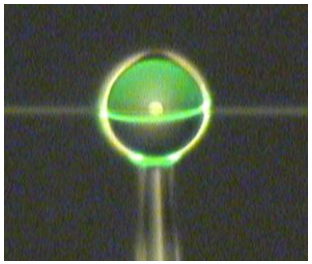
Stefan Weis,[1,2*] Rémi Rivière,[2*] Samuel Deléglise,[1,2*] Emanuel Gavartin,[1] Olivier Arcizet,[3] Albert Schliesser,[1,2] Tobias J. Kippenberg[1,2]†

10 DECEMBER 2010 VOL 330 SCIENCE www.sciencemag.org

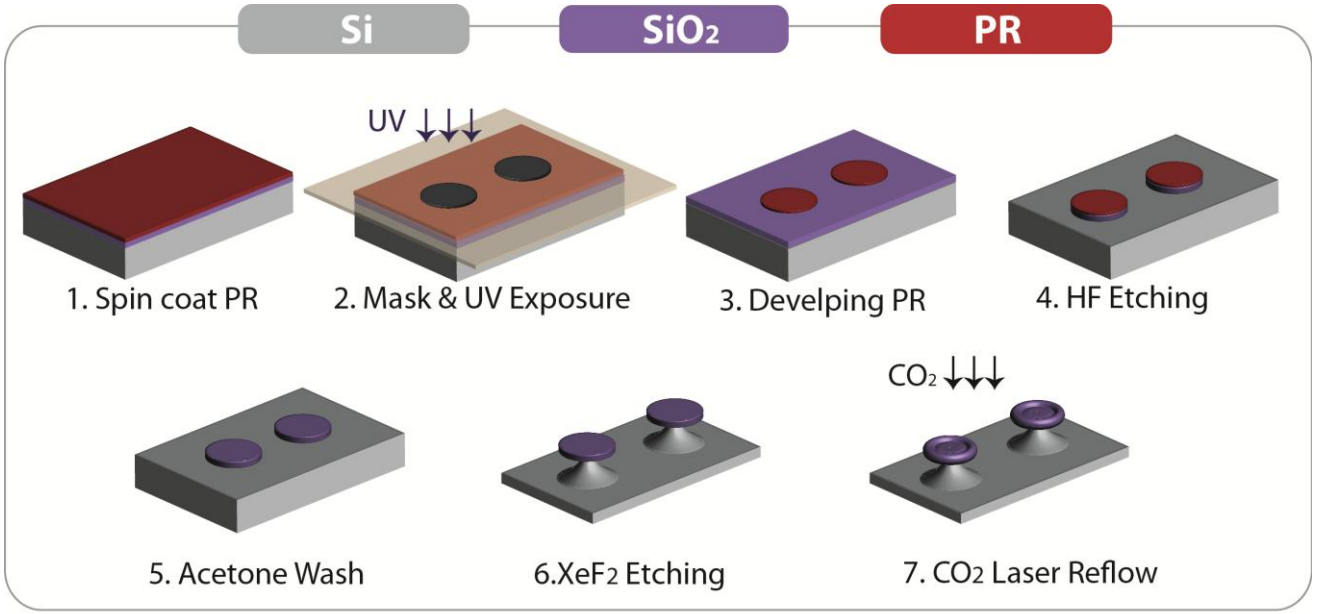
Planar silicon microrings as wavelength-multiplexed optical traps for storing and sensing particles†

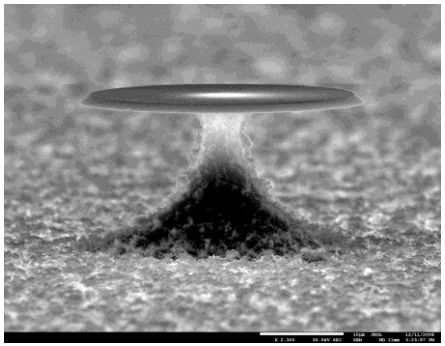
Shiyun Lin and Kenneth B. Crozier* *Lab Chip*, 2011, **11**, 4047

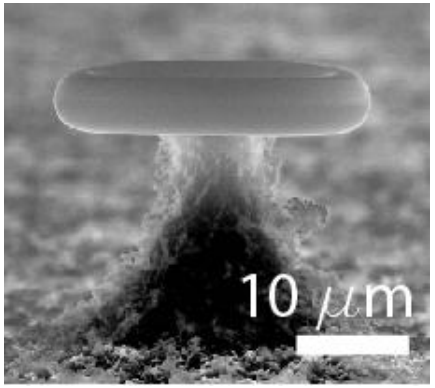


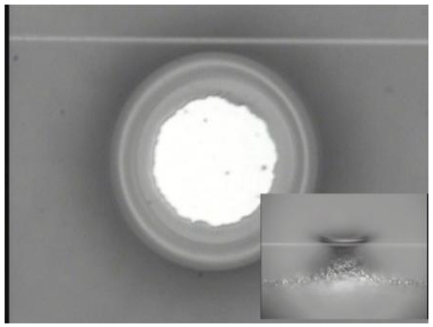


Fabrication of microtoroids

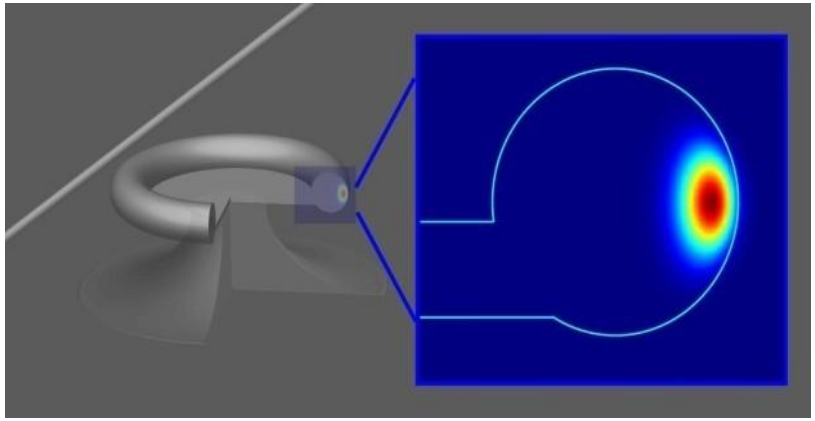


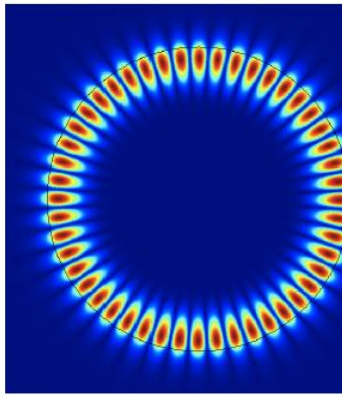


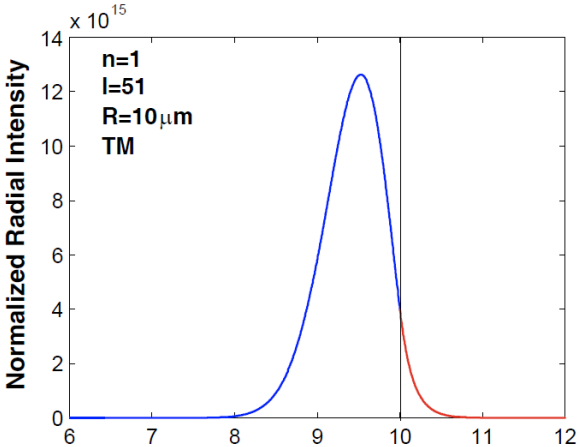




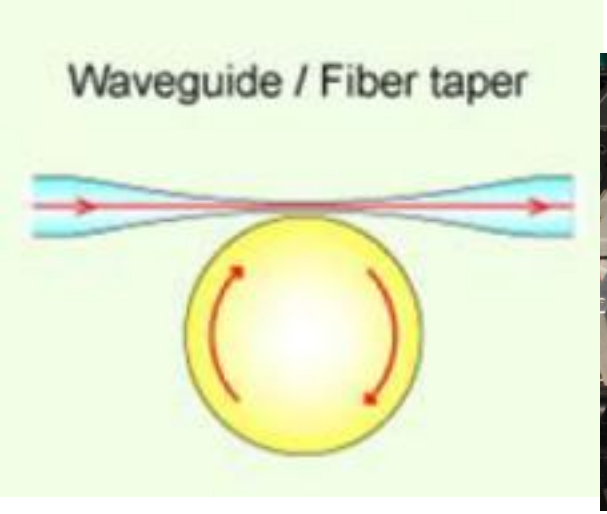
Coupling light into WGM resonators …

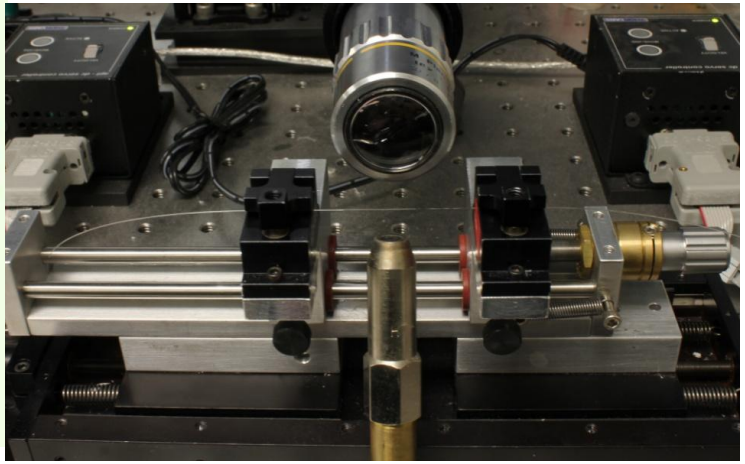


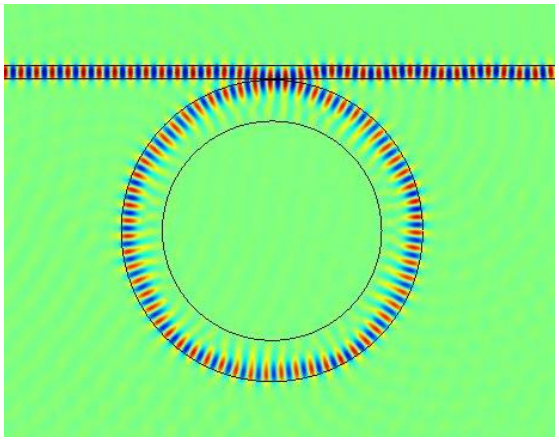




Evanescent light



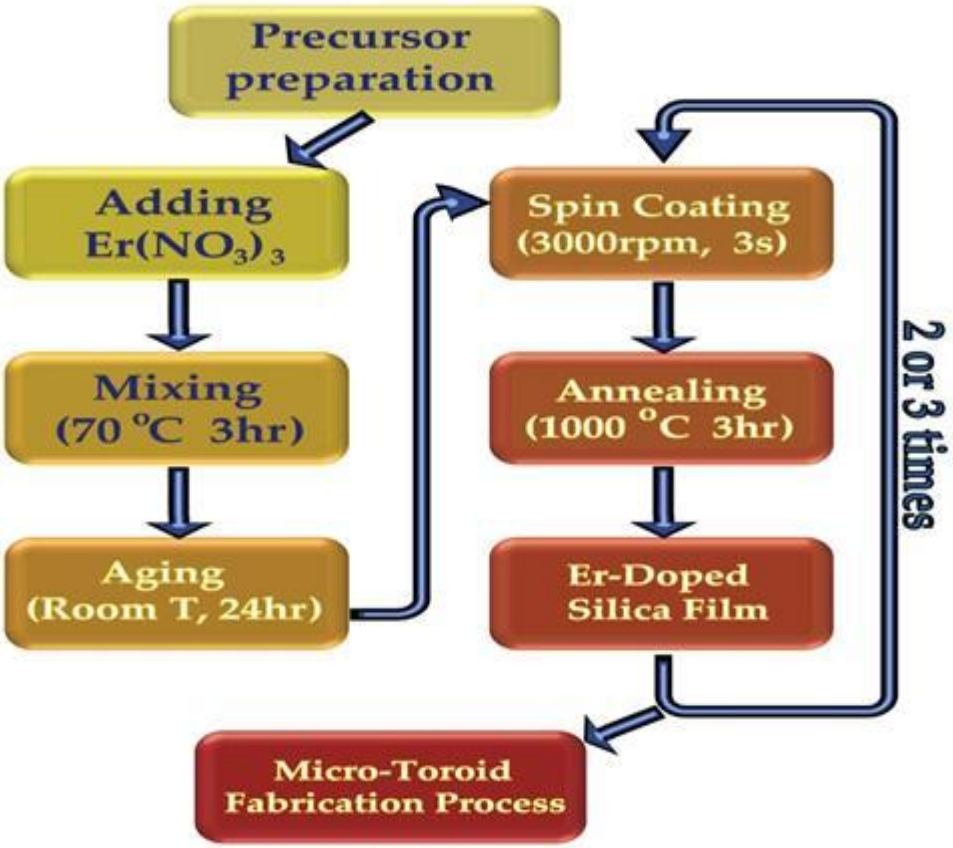


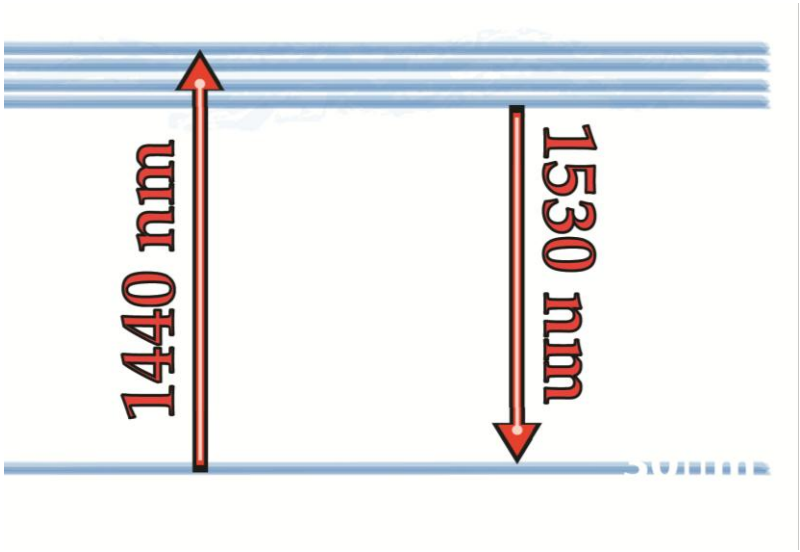


Introducing gain into WGM resonators

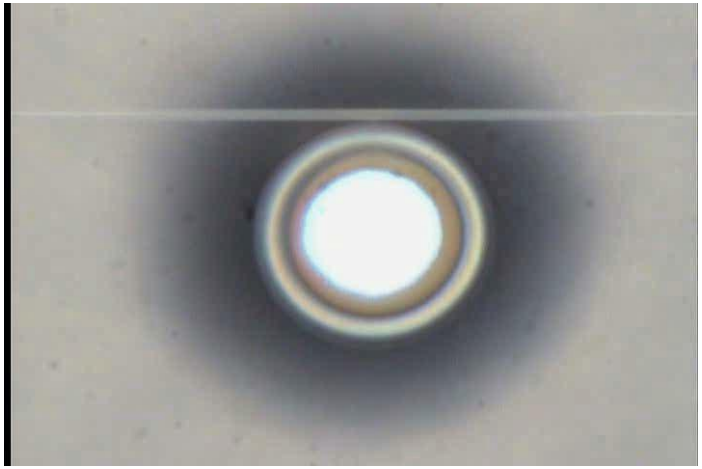
Precursor : Mixture of tetraethoxysilane, isoproponal alcohol, water and hydrochloric acid

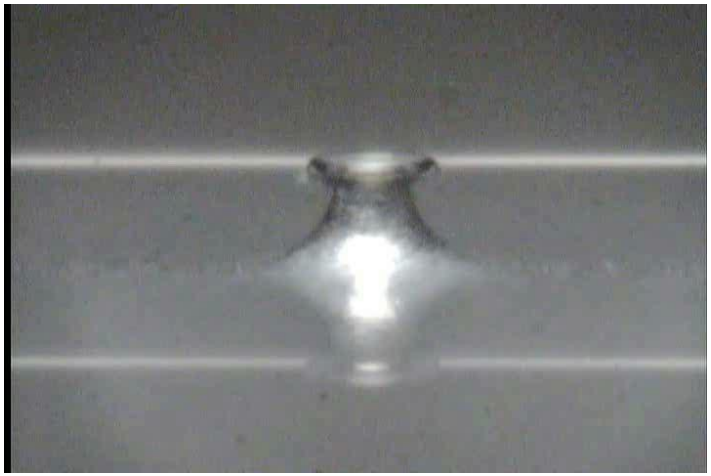
TEOS : IPA : H_2O : HCl = 0.6 : 6.5 : 0.7 : 6.1

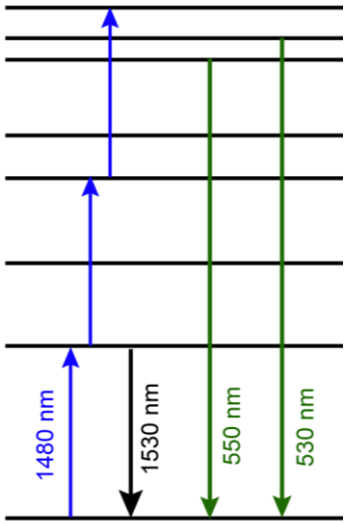


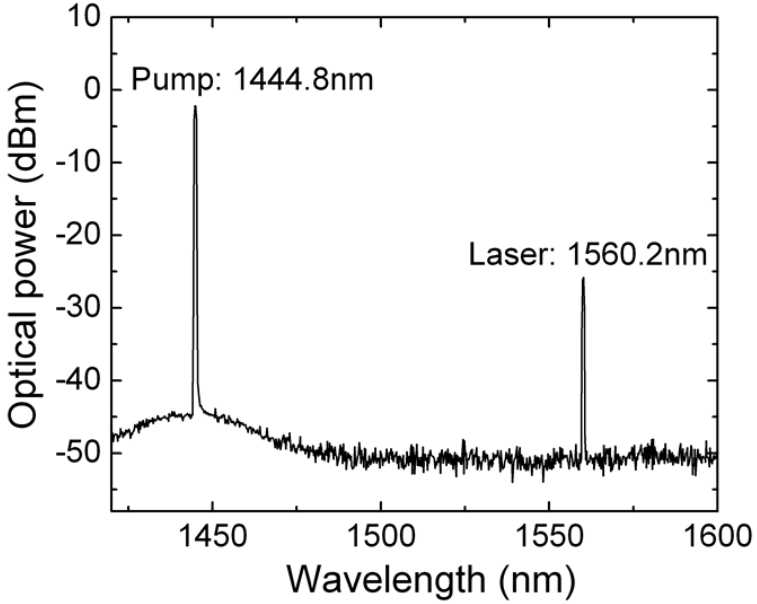


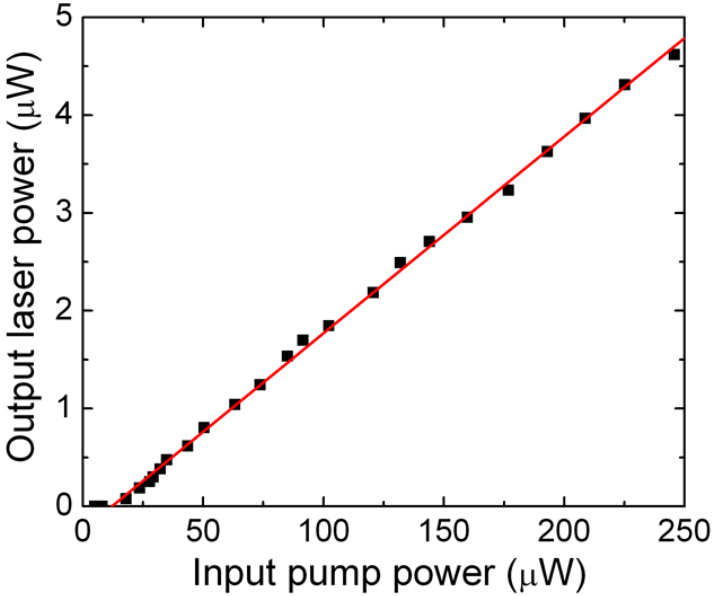
Emission from an erbium-doped microtoroid



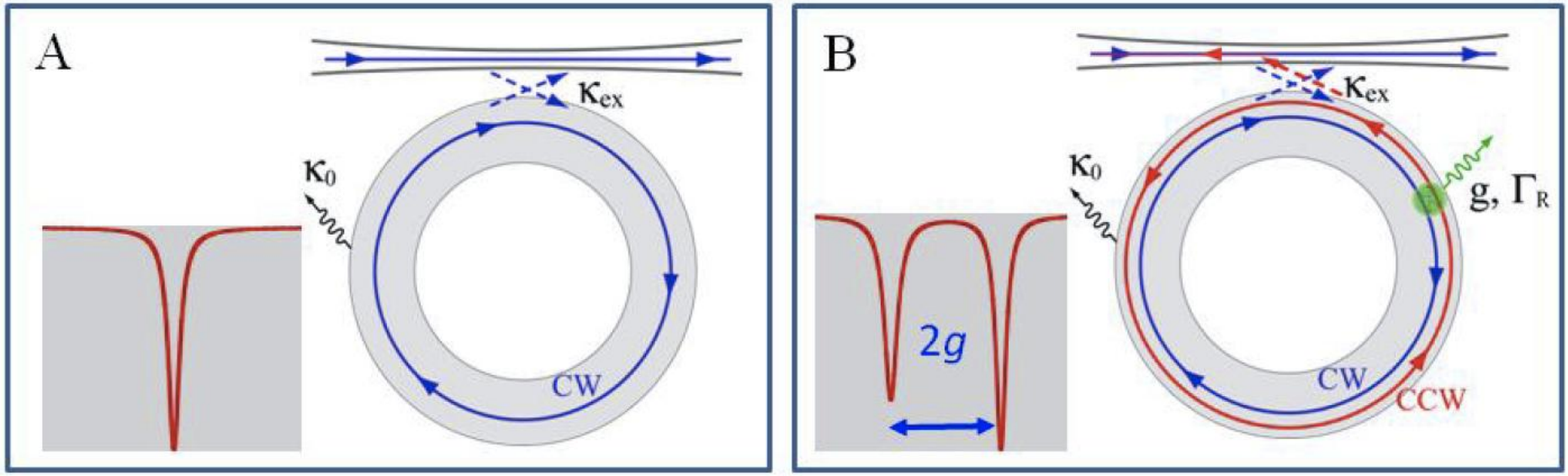








WGM: a platform for sensing



Mode splitting :

• WGM resonators supports frequency-degenerate counter-propagating modes: clockwise (CW) and counterclockwise (CCW)

• Backscattering of light from a scattering center couples CW and CCW modes lifting their degeneracy

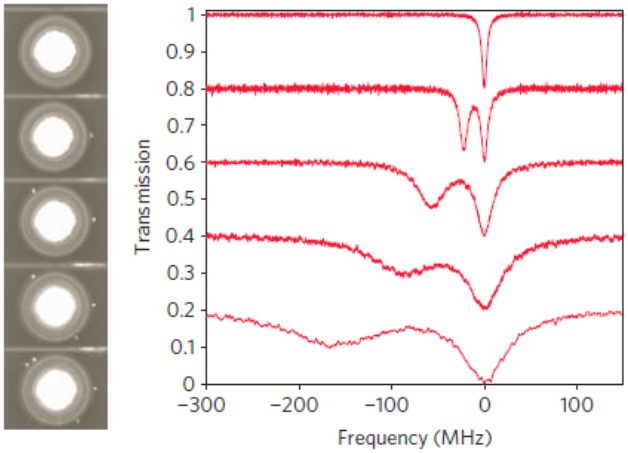
• Lifted degeneracy manifests itself as a transition from one resonant WGM to a doublet (two WGM resonances) in the transmission spectra.

Our contributions to the field …

LETTERS
PUBLISHED ONLINE: 13 DECEMBER 2009 | DOI: 10.1038/NPHOTON.2009.237
nature photonics

On-chip single nanoparticle detection and sizing by mode splitting in an ultrahigh-Q microresonator

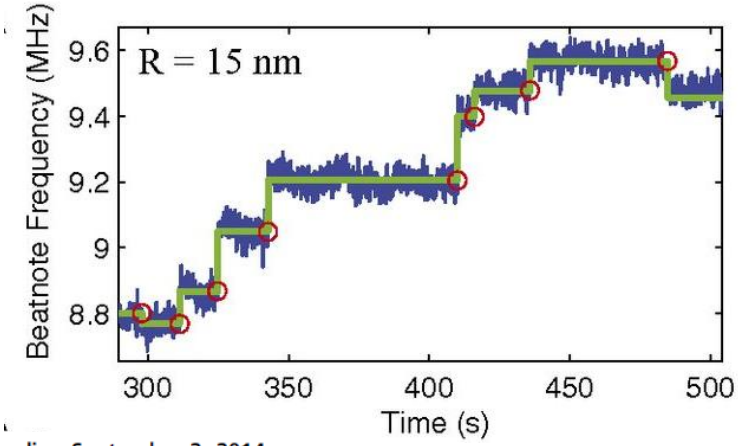
Jiangang Zhu[1], Sahin Kaya Ozdemir[1], Yun-Feng Xiao[1†], Lin Li[2], Lina He[1], Da-Ren Chen[2] and Lan Yang[1]*

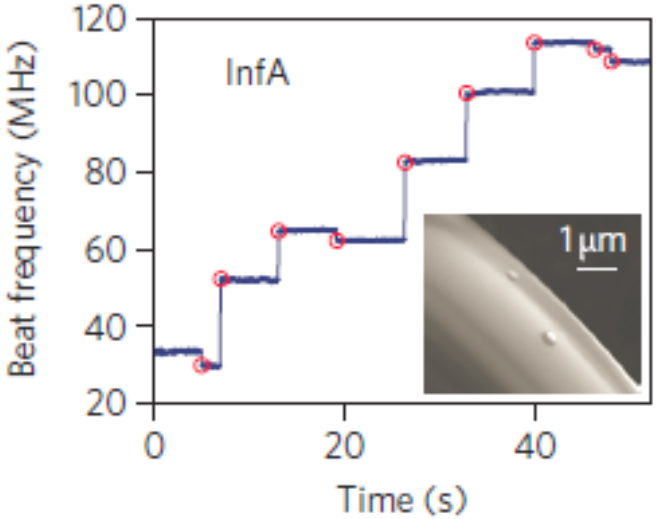


LETTERS
PUBLISHED ONLINE: 26 JUNE 2011 | DOI: 10.1038/NNANO.2011.99
nature nanotechnology

Detecting single viruses and nanoparticles using whispering gallery microlasers

Lina He, Şahin Kaya Özdemir, Jiangang Zhu, Woosung Kim and Lan Yang*





PNAS Published online September 2, 2014

Highly sensitive detection of nanoparticles with a self-referenced and self-heterodyned whispering-gallery Raman microlaser

Şahin Kaya Özdemir[a,1,2], Jiangang Zhu[a,1], Xu Yang[b], Bo Peng[a], Huzeyfe Yilmaz[a], Lina He[a], Faraz Monifi[a], Steven He Huang[a], Gui Lu Long[b], and Lan Yang[a,2]

Agenda

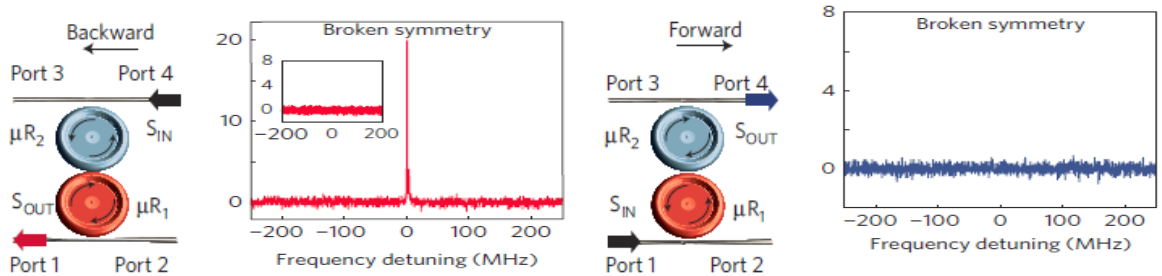
1. PT and EP in optical systems: Brief review
2. Whispering-gallery-mode (WGM) resonators
3. PT-symmetric WGM microresonators
4. Loss-induced suppression and revival of lasing at an EP
5. Chiral modes and directional emission at EPs
6. Conclusions

Our contributions to the field …

ARTICLES
PUBLISHED ONLINE: 6 APRIL 2014 | DOI: 10.1038/NPHYS2927
nature physics

Parity-time-symmetric whispering-gallery microcavities

Bo Peng[1†], Şahin Kaya Özdemir[1*†], Fuchuan Lei[1,2], Faraz Monifi[1], Mariagiovanna Gianfreda[3,4], Gui Lu Long[2,5], Shanhui Fan[6], Franco Nori[7,8], Carl M. Bender[3] and Lan Yang[1*]

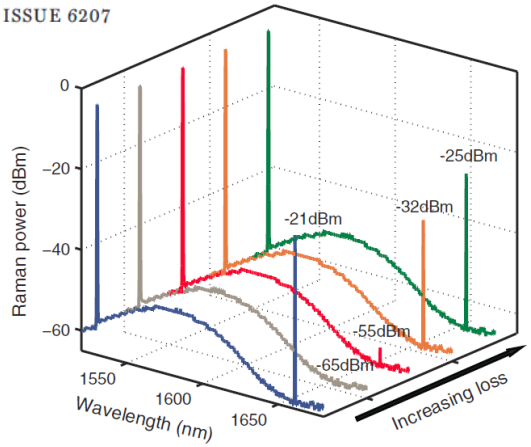


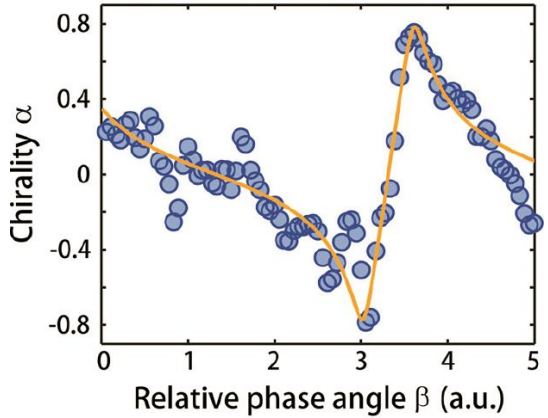
OPTICS sciencemag.org SCIENCE

Loss-induced suppression and revival of lasing

B. Peng,[1*] Ş. K. Özdemir,[1*†] S. Rotter,[2] H. Yilmaz,[1] M. Liertzer,[2] F. Monifi,[1] C. M. Bender,[3] F. Nori,[4,5] L. Yang[1†]

328 17 OCTOBER 2014 • VOL 346 ISSUE 6207



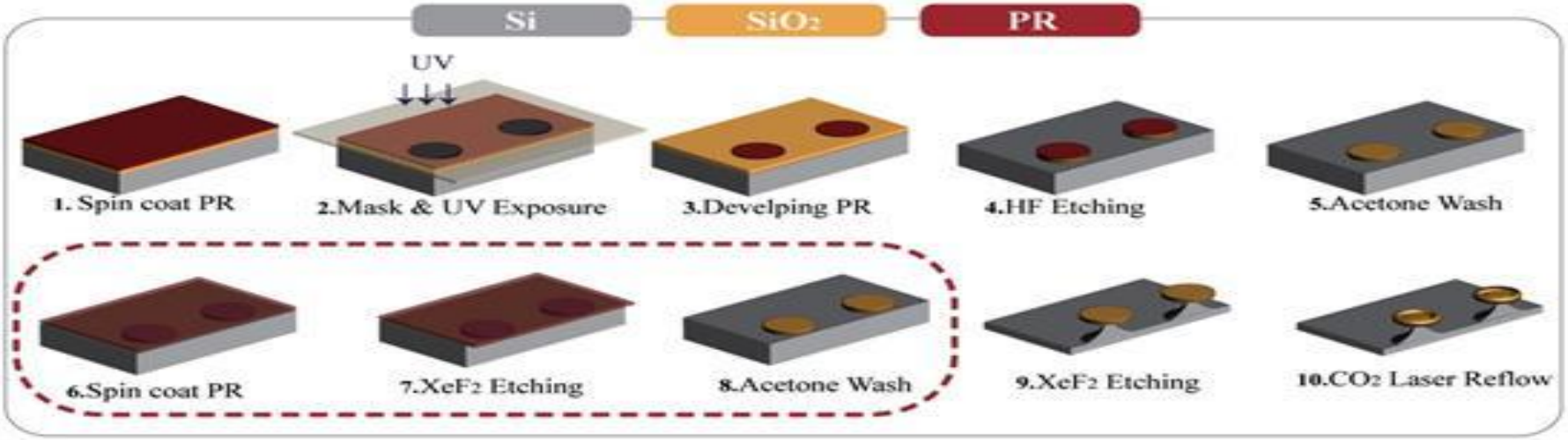


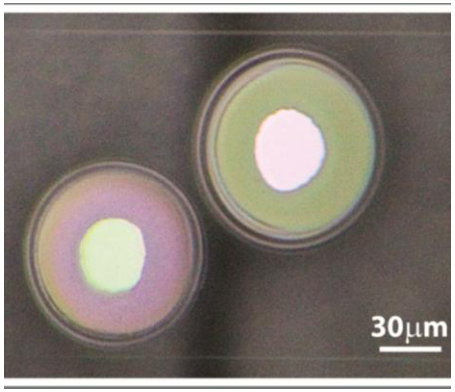
Chiral modes and directional lasing at exceptional points

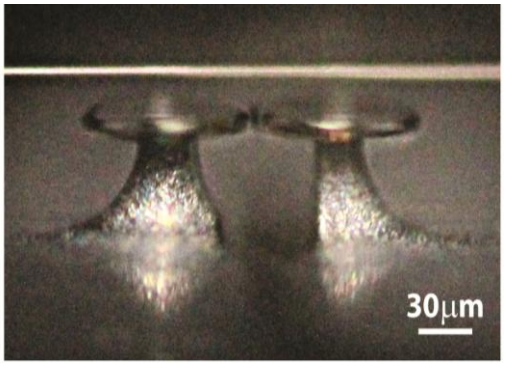
Bo Peng[a,1], Şahin Kaya Özdemir[a,1,2], Matthias Liertzer[b], Weijian Chen[a], Johannes Kramer[c], Huzeyfe Yılmaz[a], Jan Wiersig[c], Stefan Rotter[b], and Lan Yang[a,2]

PNAS | June 21, 2016 | vol. 113 | no. 25 | 6845–6850

Fabrication of edge microtoroids

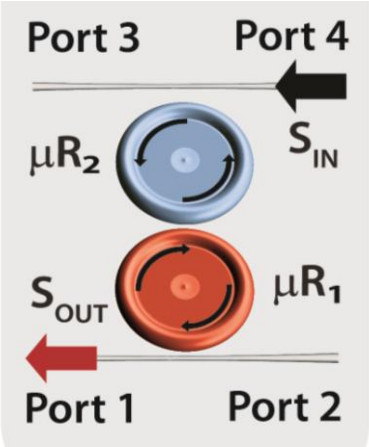


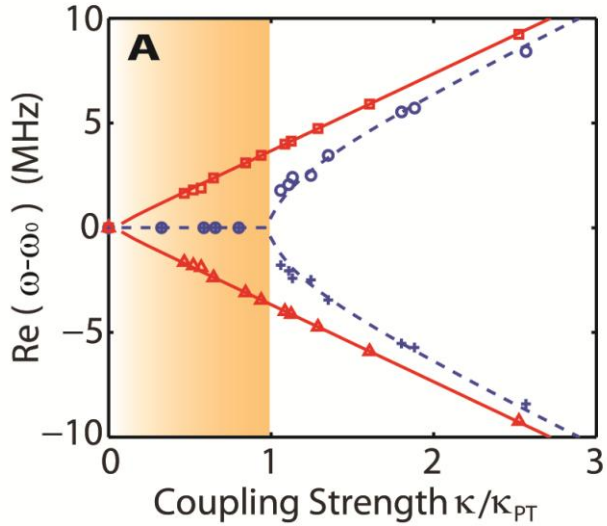


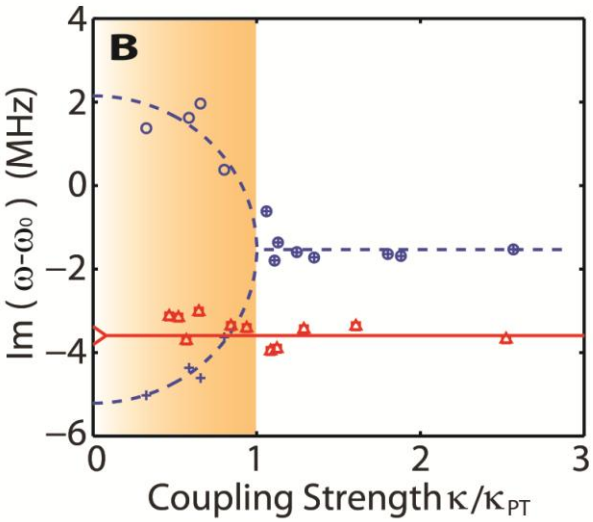


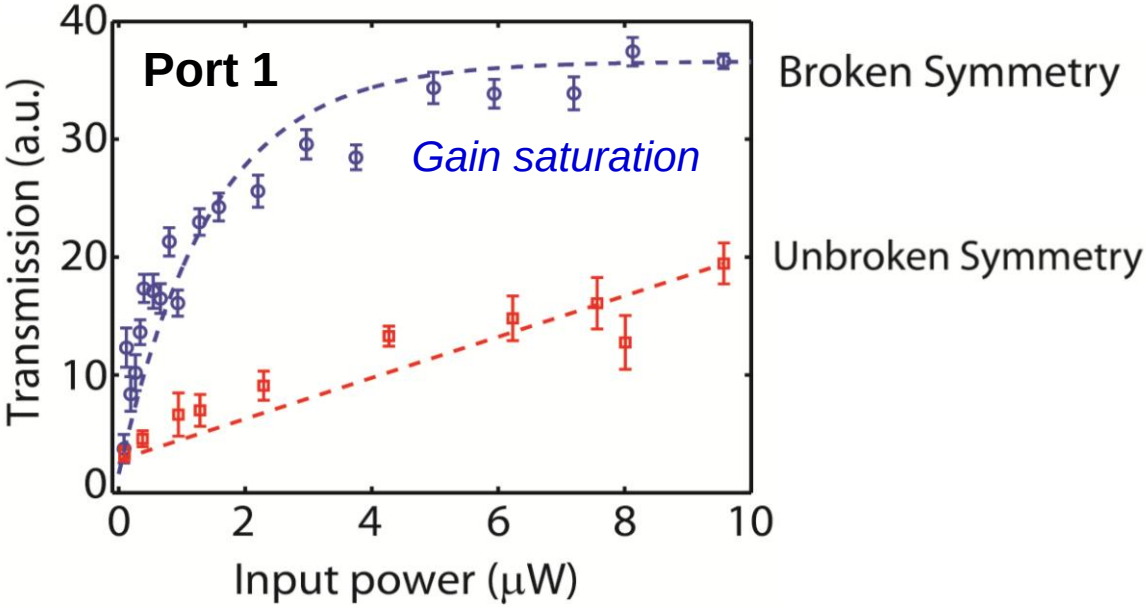
PT-transition and input-output relation

Nature Physics, 10, 394-398 (2014)



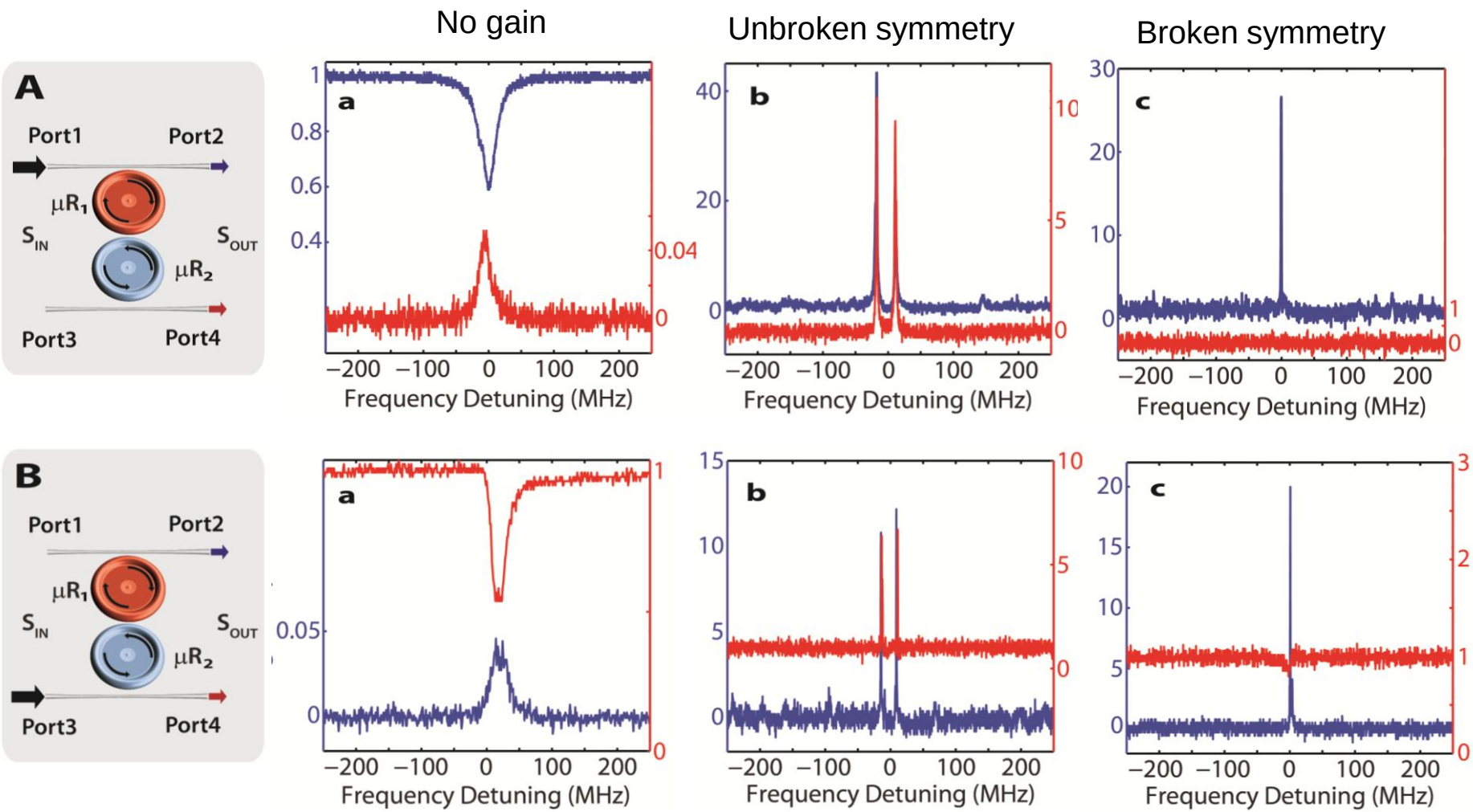






Field localization enhances nonlinearity

Nature Physics, 10, 394-398 (2014)



Regardless of which input is used, field is localized in the resonator with gain

Nonreciprocal light transmission

Any time-independent linear system, described by a symmetric electric permittivity tensor and a symmetric magnetic permeability tensor is constrained by the Lorentz reciprocity theorem. Such a system is reciprocal in the sense that its scattering matrix is symmetric.

The reciprocity theorem applies even when the system has gain or loss.

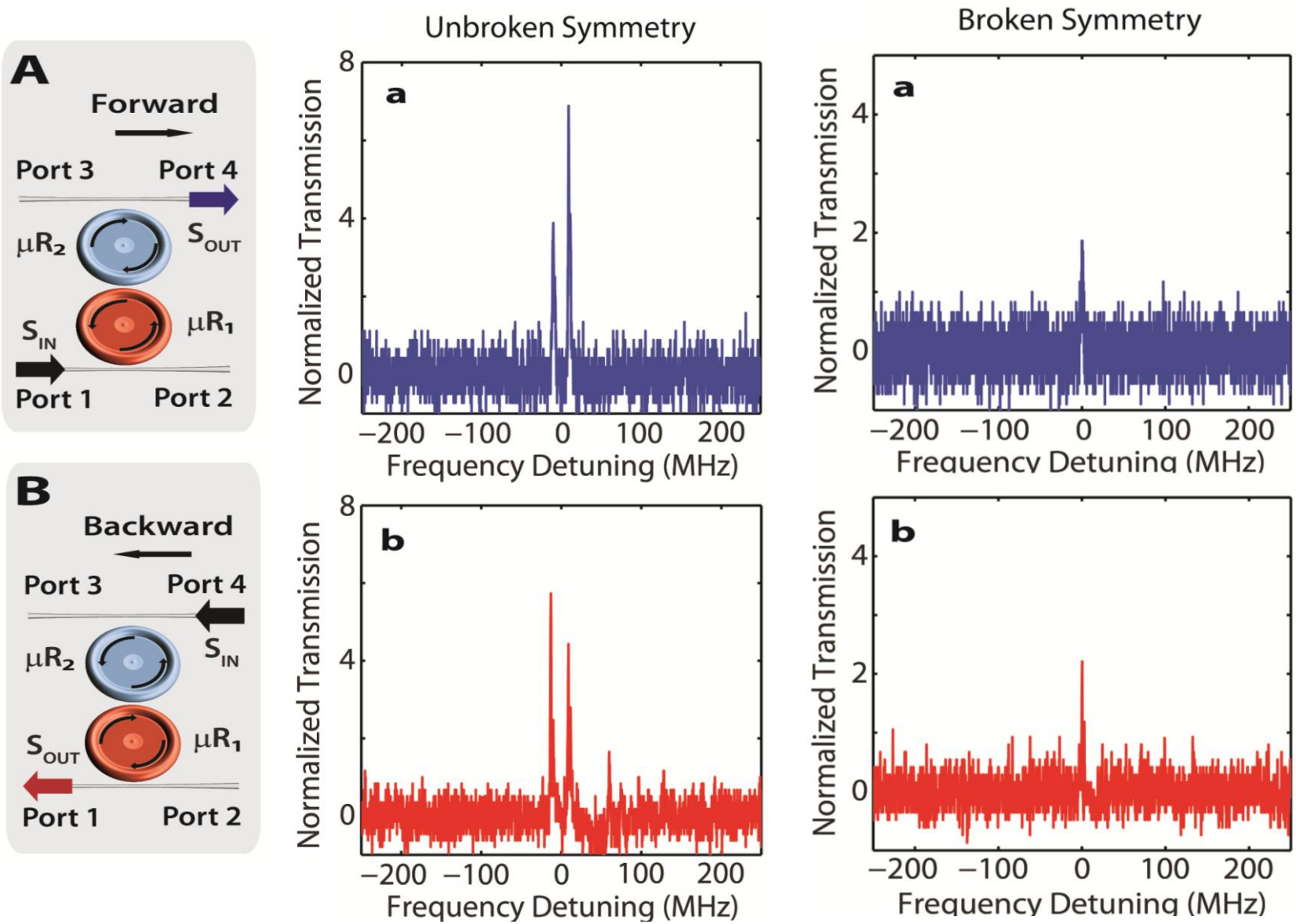
Reciprocities are broken for magneto-optical, as well as time-dependent or nonlinear structures

S. Fan et al., Science 335, 38 (2012)

How does the observed nonlinearity affect light transport in PT-symmetric WGM microcavities ?

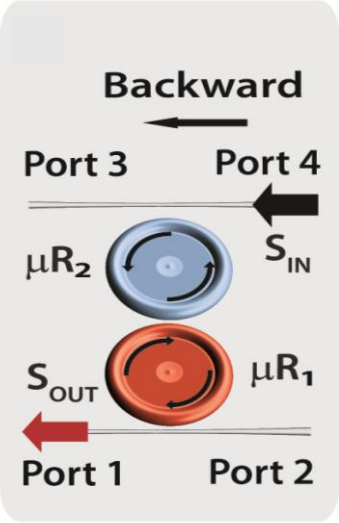
Linear region (low input power)

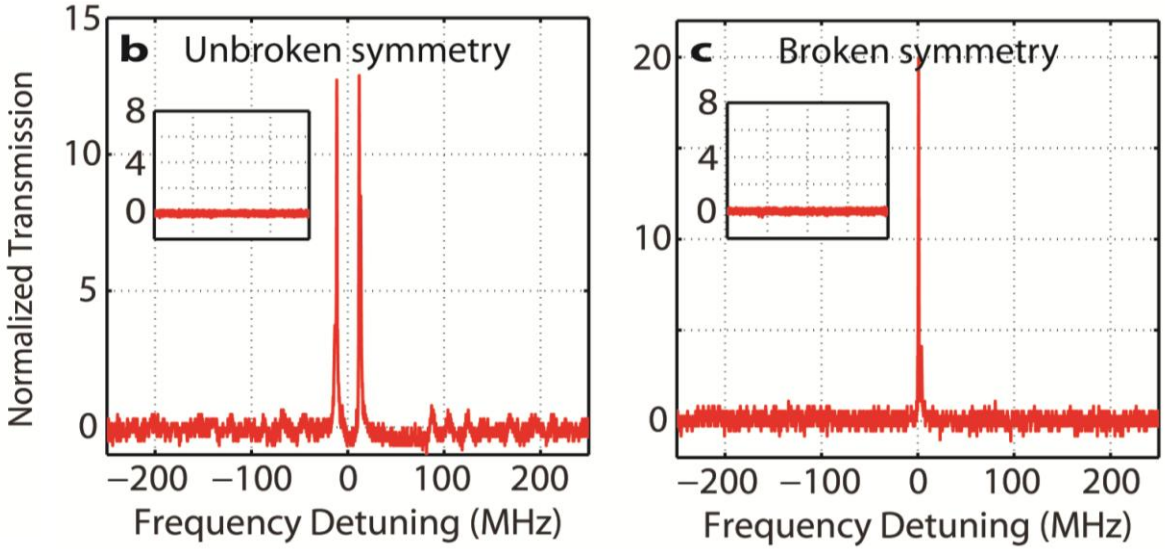
Nature Physics, 10, 394-398 (2014)

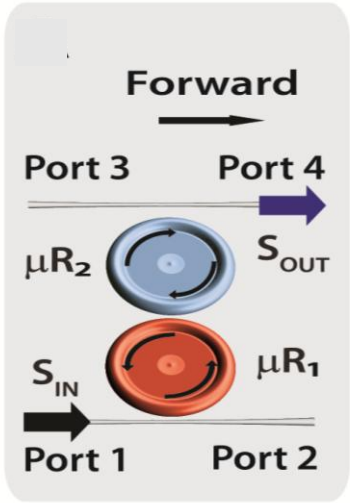


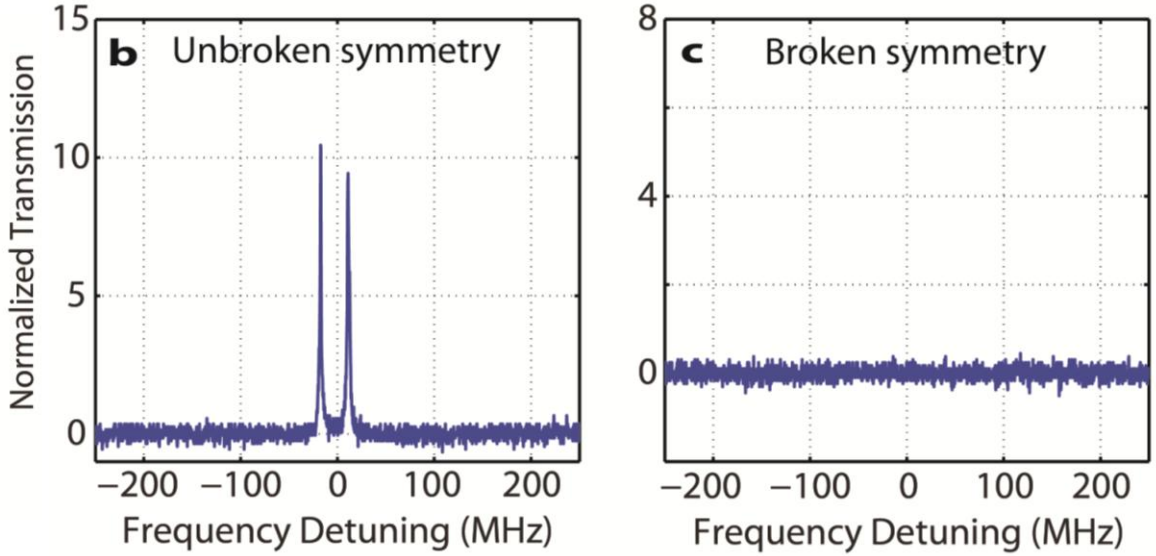
Nonlinear region (high input power)

Nature Physics, 10, 394-398 (2014)

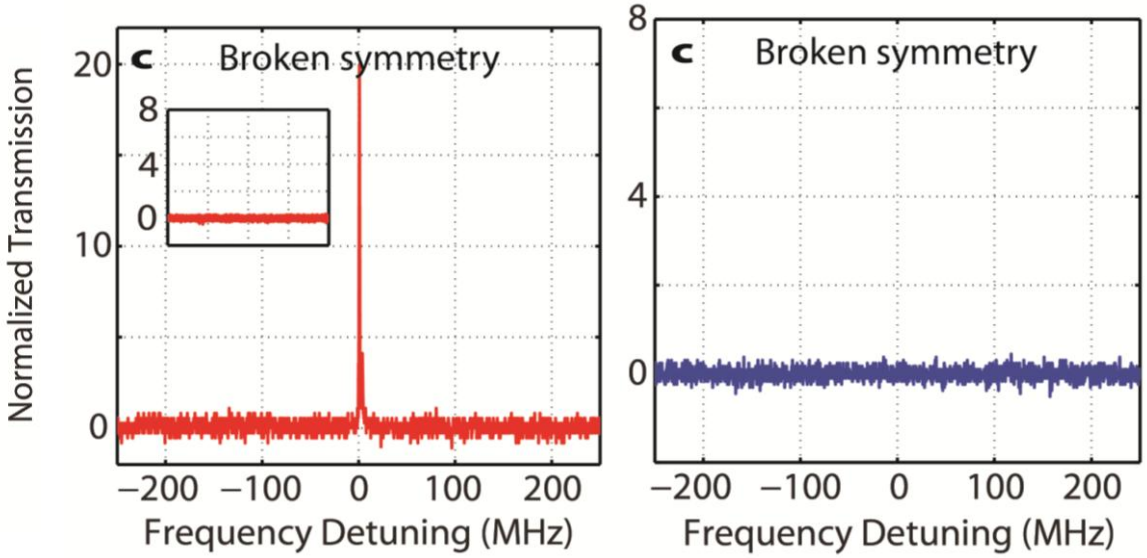








Nonreciprocal light transmission



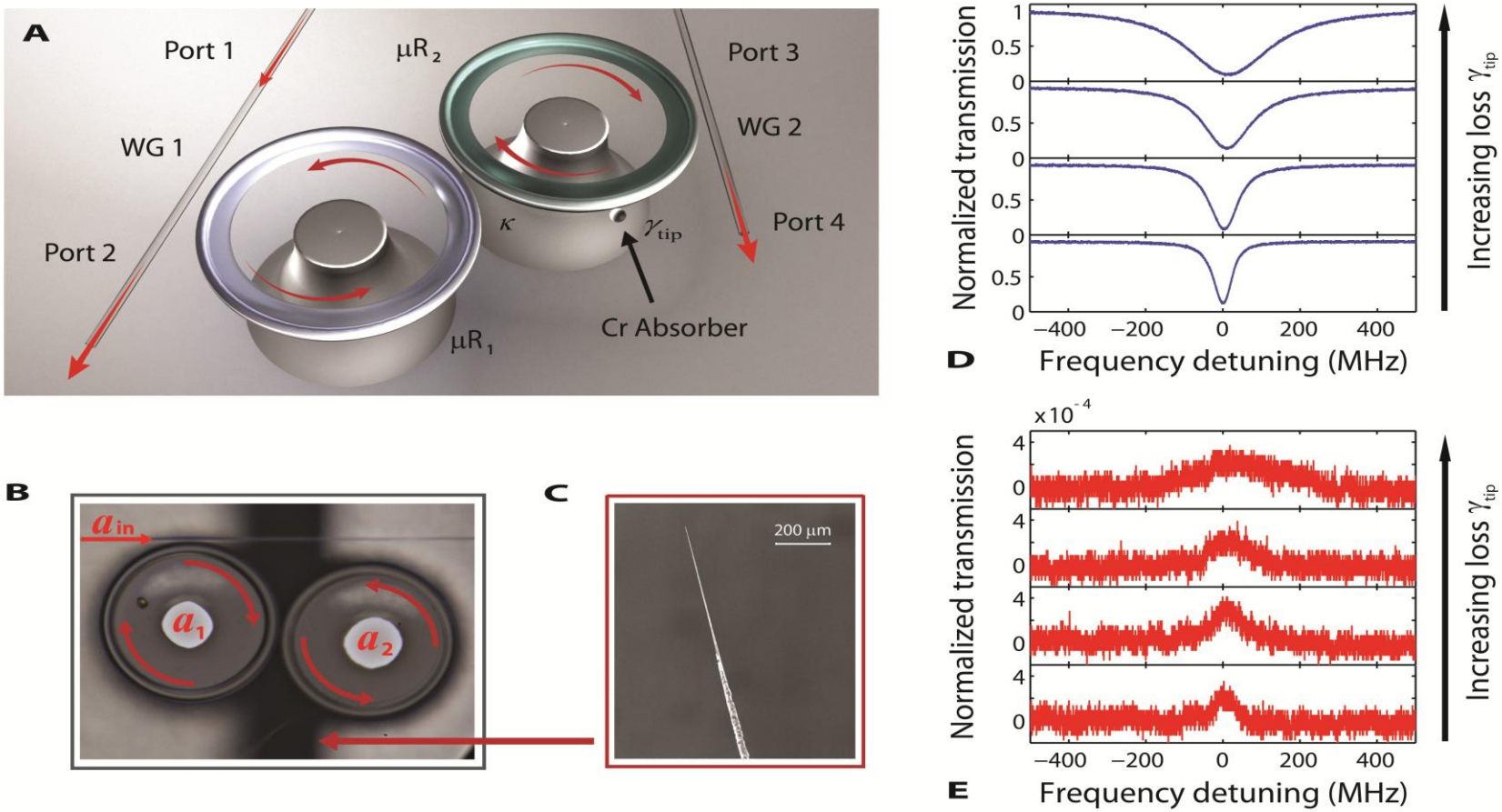
- Complete absence of signal in one direction
- Less than 2μW of power to observe nonreciprocity
- No magnetic field
- First nonreciprocal light transmission based on PT-symmetric concepts
- Direct experimental proof that PT-symmetry breaking is not sufficient for nonreciprocity

Agenda

1. PT and EP in optical systems: Brief review
2. Whispering-gallery-mode (WGM) resonators
3. PT-symmetric WGM microresonators
4. Loss-induced suppression and revival of lasing at an EP
5. Chiral modes and directional emission at EPs
6. Conclusions

Coupled resonators in the vicinity of EP

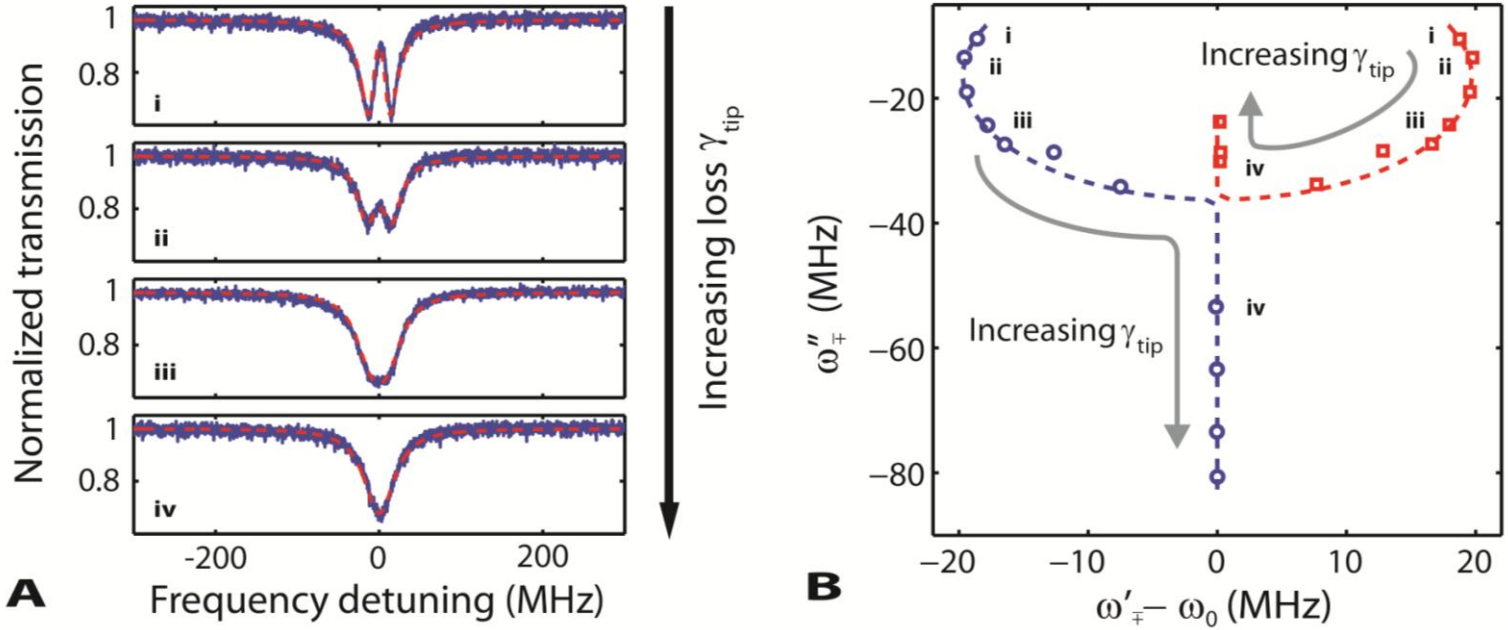
Science, 346, 328-332 (2014)



- Two coupled passive microtoroids
- Loss induced by introducing a chromium tip
- Loss is reflected in the broadening of linewidth

Coupled resonator in the vicinity of EP

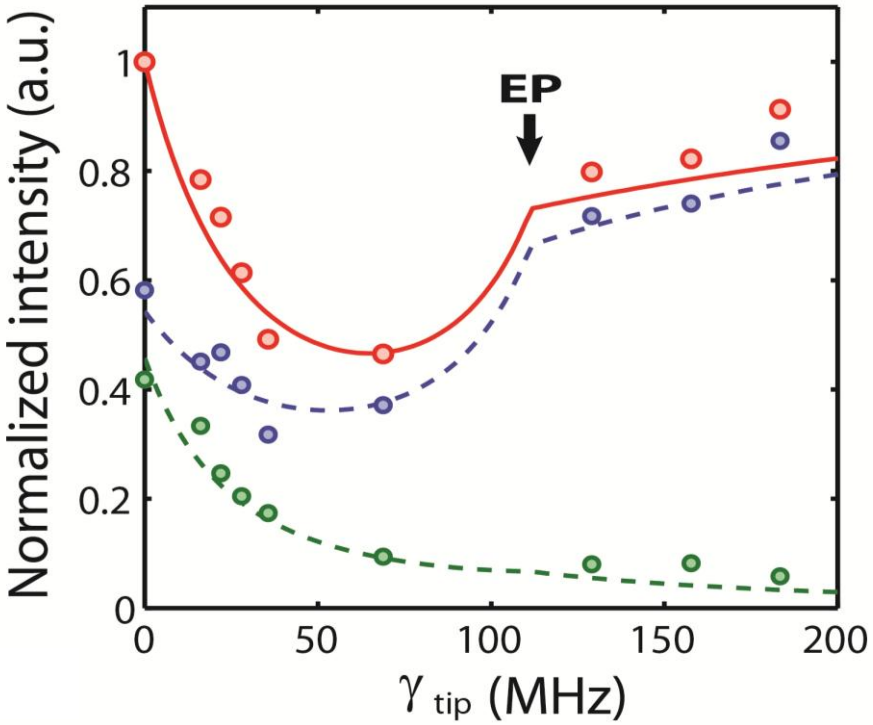
Science, 346, 328-332 (2014)

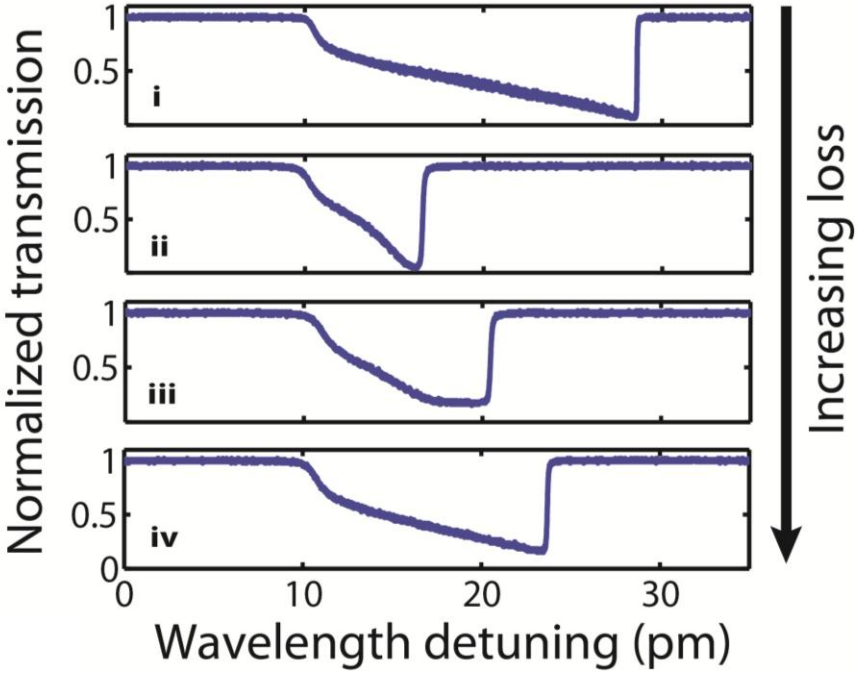


- Real parts of supermodes coalesce Imaginary parts bifurcate
- One of the modes become more lossy while the other less lossy
- Symmetry breaking: EP

Coupled resonators in the vicinity of EP

Science, 346, 328-332 (2014)

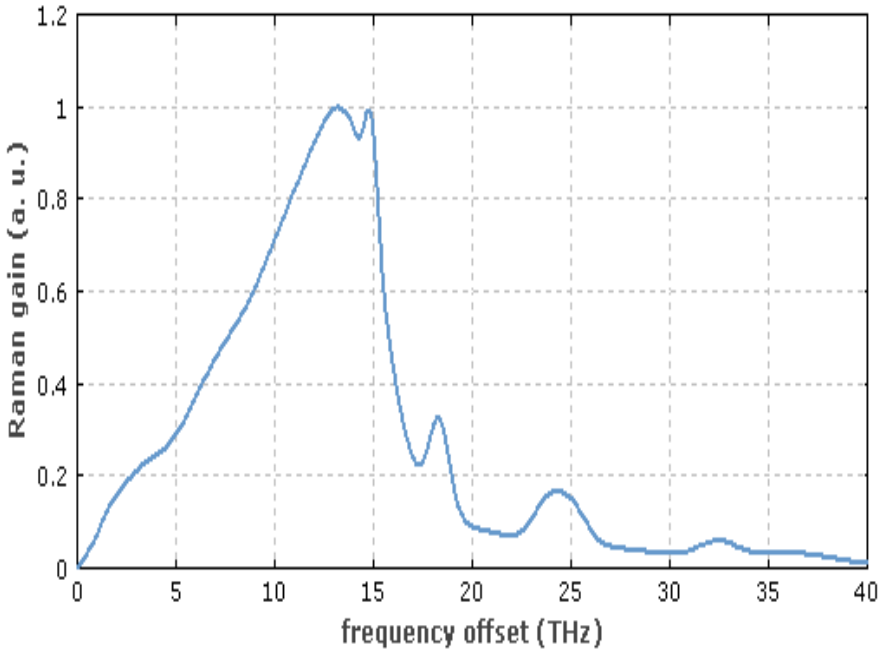


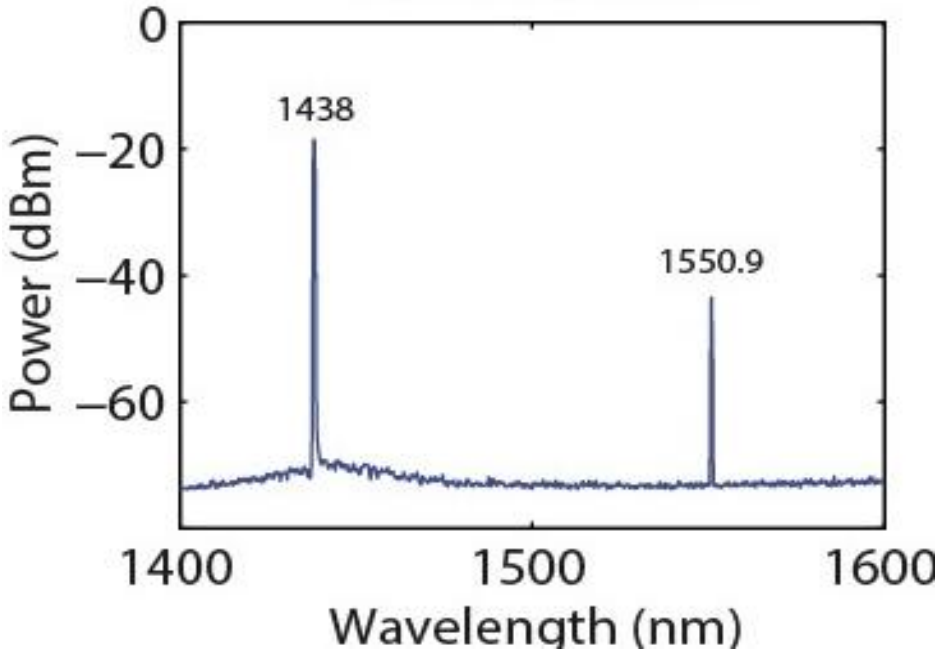


- Loss induced transparency
- Increasing loss recovers the thermal nonlinearity

Loss-induced Recovery of Lasing

Science, 346, 328-332 (2014)

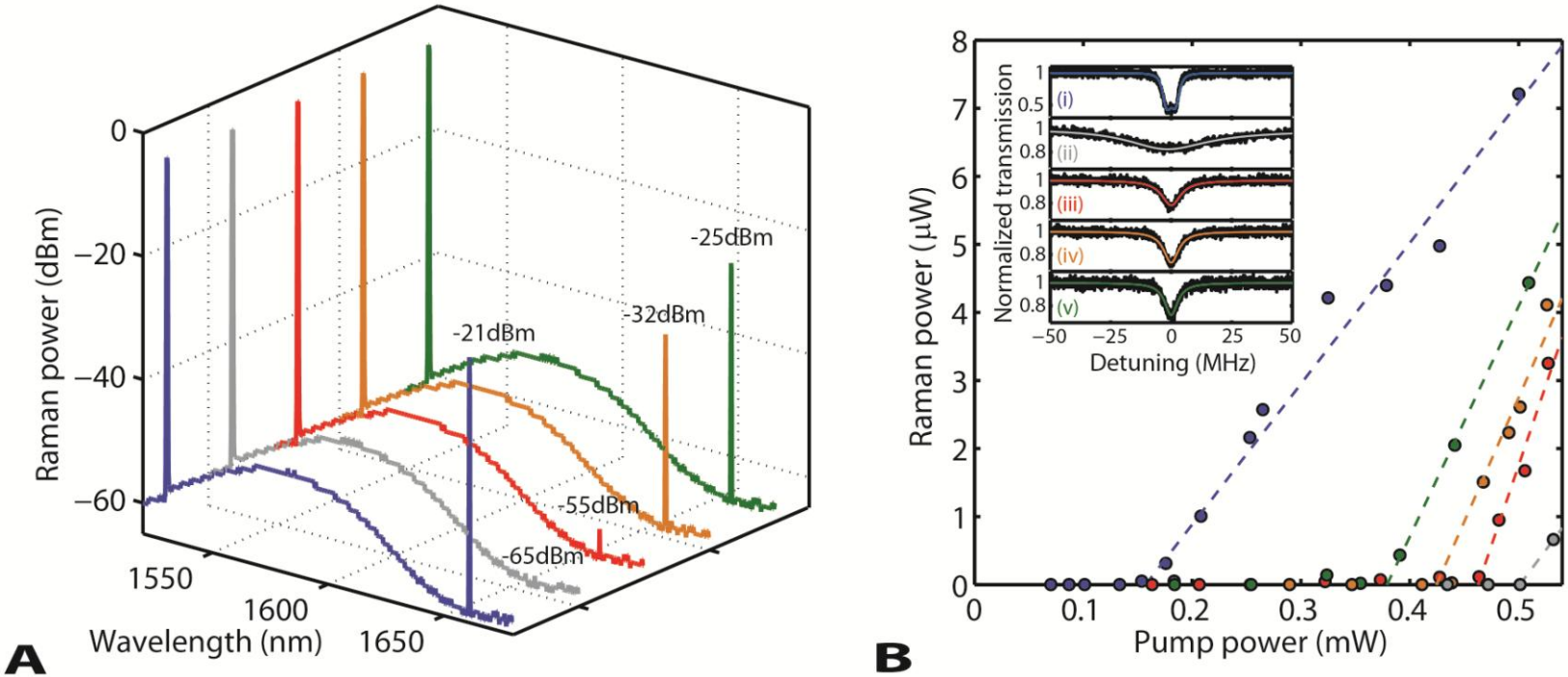




- Raman process in silica : Maximum gain at ~ 13 THz
- With in 1450 nm band leads to Raman lasing in the 1550 nm band
- Lasing threshold scales V/Q^2 : Intracavity field intensity

Loss-induced Recovery of Lasing

Science, 346, 328-332 (2014)



- When loss is below a critical value, Raman lasing is annihilated
- Increasing loss pushes the system close to the EP, and localizes the field in the less lossy resonator
- Beyond EP-phase transition point, increasing loss helps to recover Raman lasing

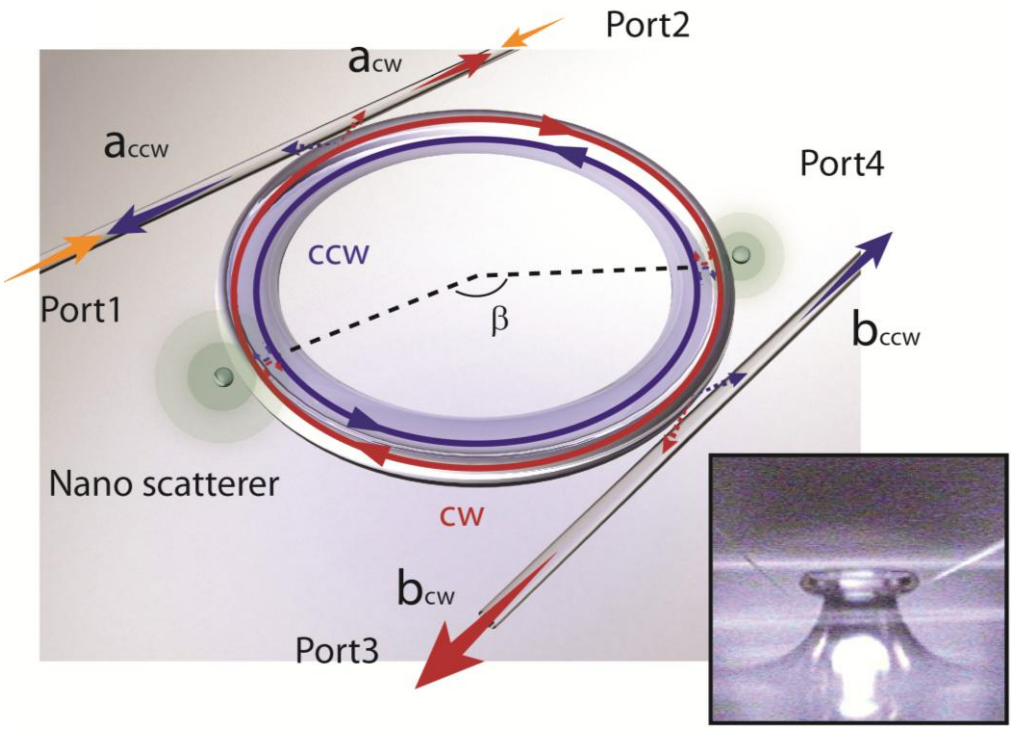
Agenda

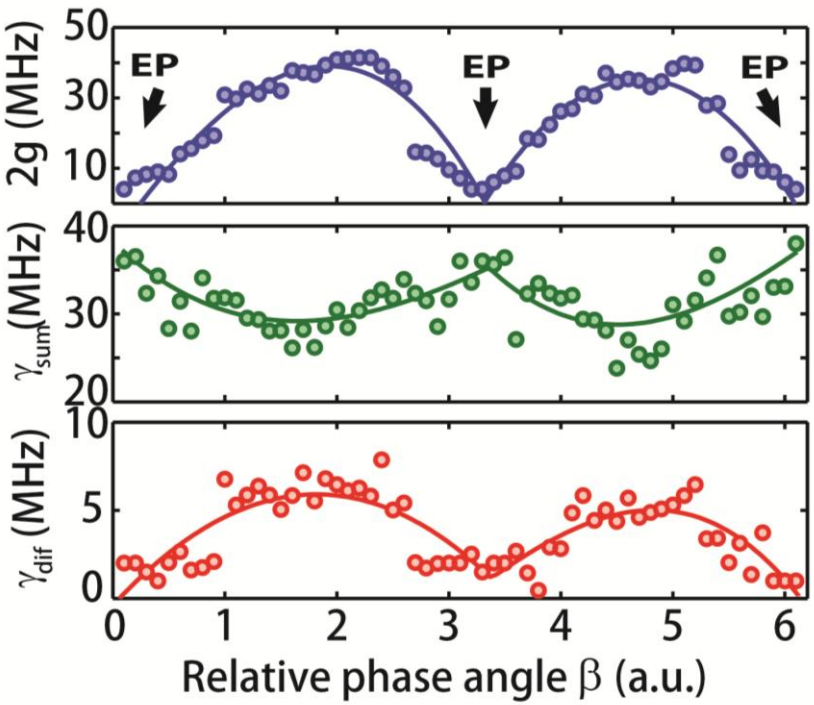
1. PT and EP in optical systems: Brief review
2. Whispering-gallery-mode (WGM) resonators
3. PT-symmetric WGM microresonators
4. Loss-induced suppression and revival of lasing at an EP
5. Chiral modes and directional emission at EPs
6. Conclusions

Directionality and chiral modes at an EP

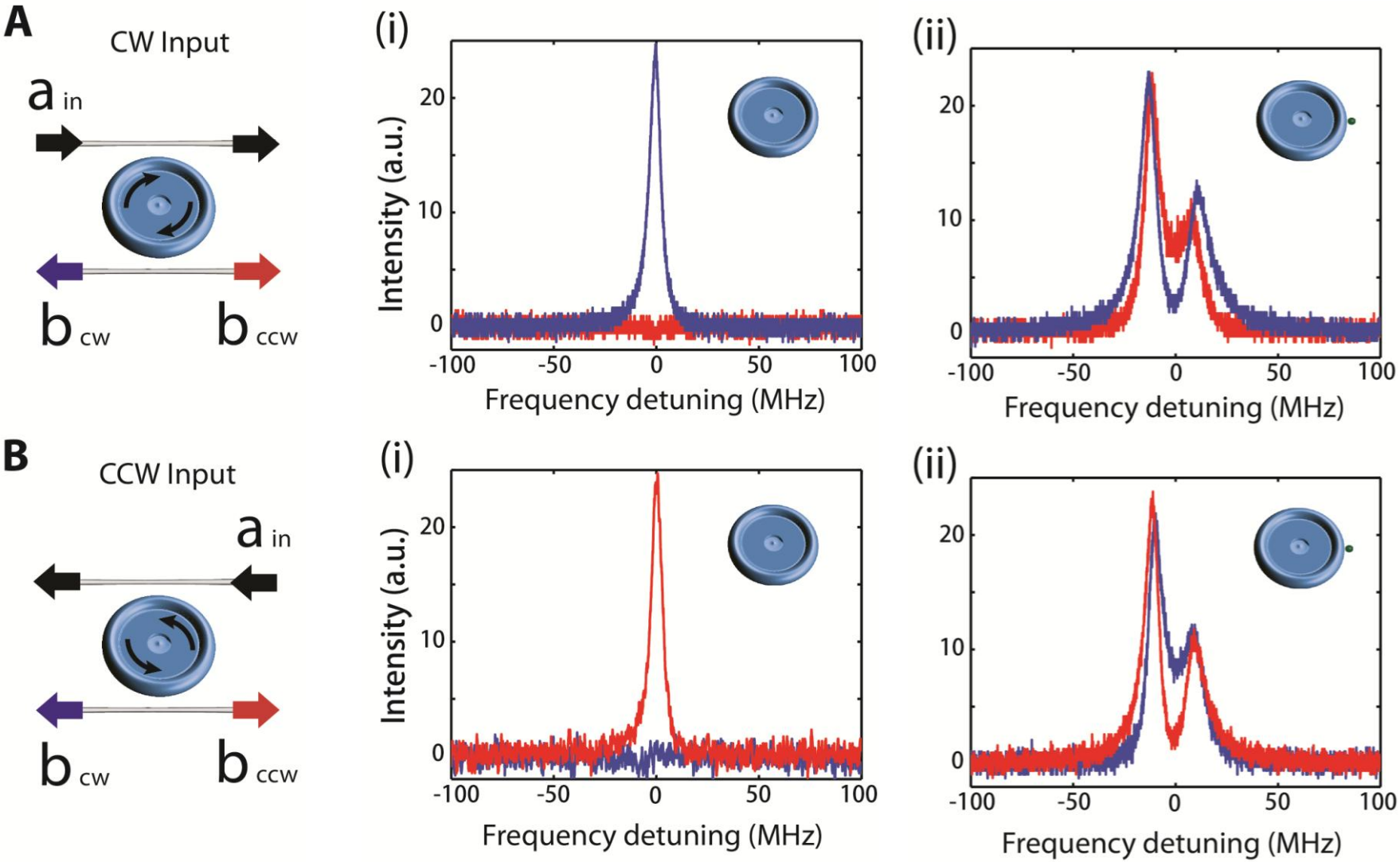
[PNAS 113, 201603318 (2016)]

- WGM resonators support counter-propagating modes of the same frequency
- Light input in one direction can be scattered to the other by scatterers
- Can we control the propagation direction of light inside the resonator?

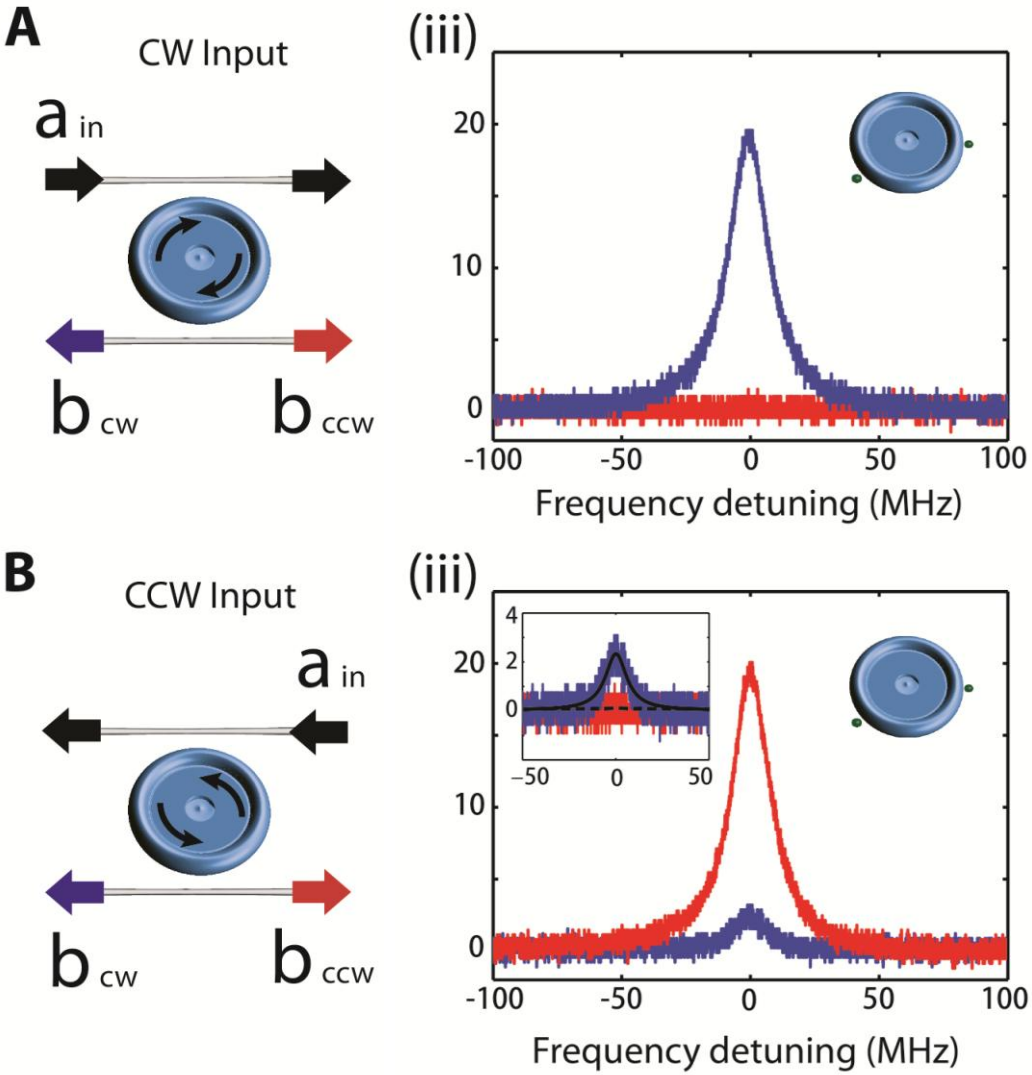




Mode splitting: light outcouples in both direction



Asymmetric backreflection at an EP



Chirality ~ 0.86

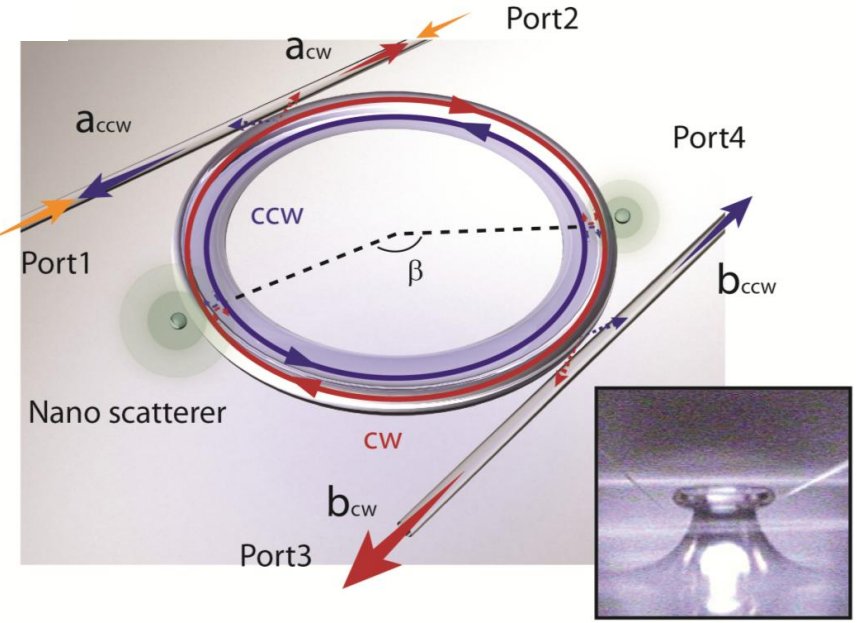
- No splitting: Exceptional point
- Only one eigenvector exists
- Transmission curves for different input ports are the same: Reciprocity
- Backscattering (reflection) curves for different input ports are different: Asymmetric backreflection

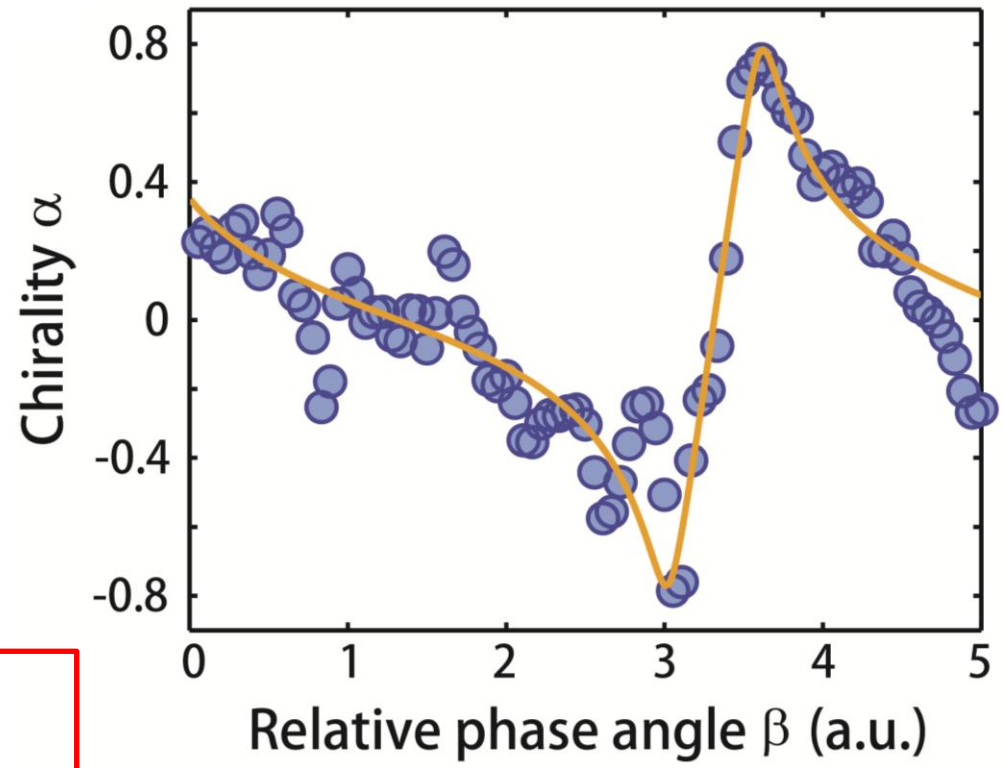
J. Wiersig's talk [PRA 2011]

Chirality

Chirality is an intrinsic property of a mode independent of input direction

Chirality: an intrinsic property of a mode

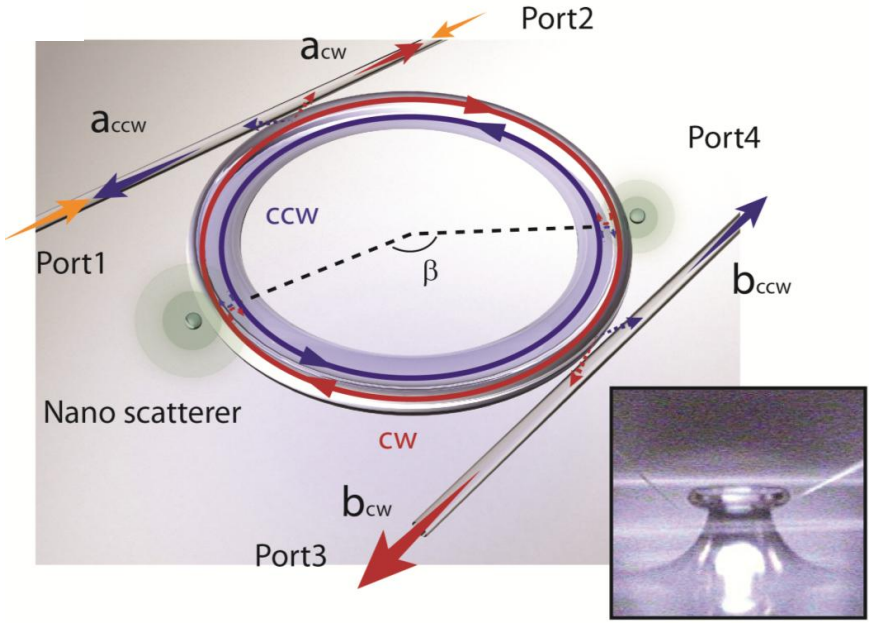


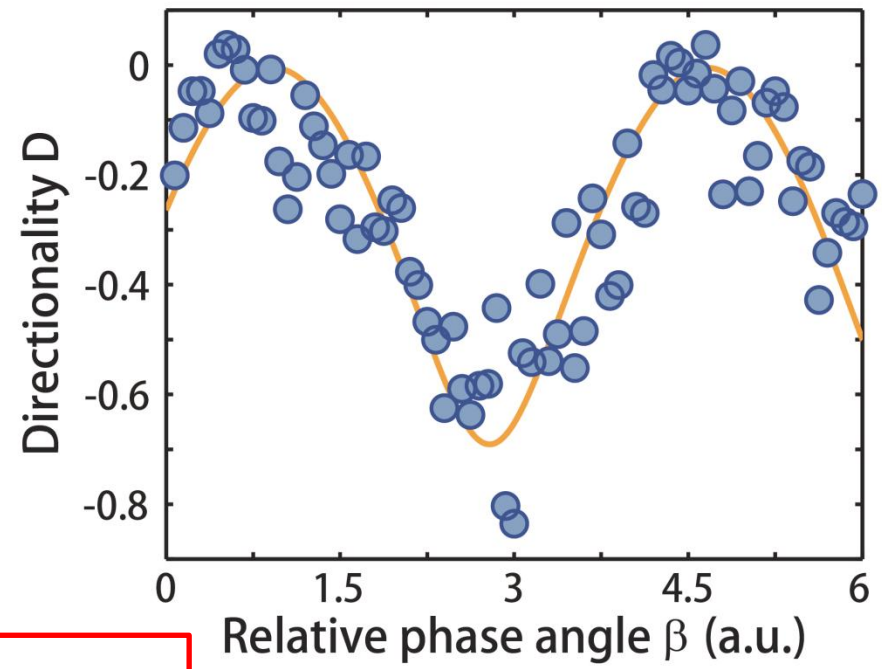


$$\alpha = \frac{I_{14} - I_{23}}{I_{14} + I_{23}}$$

- Chirality equals zero: Backreflection is the same for both input sides.
- Chirality is maximum (+/- one) at an EP.
- Observing both +/- values implies the presence of two EPs.

Directionality: sense of rotation of the cavity light

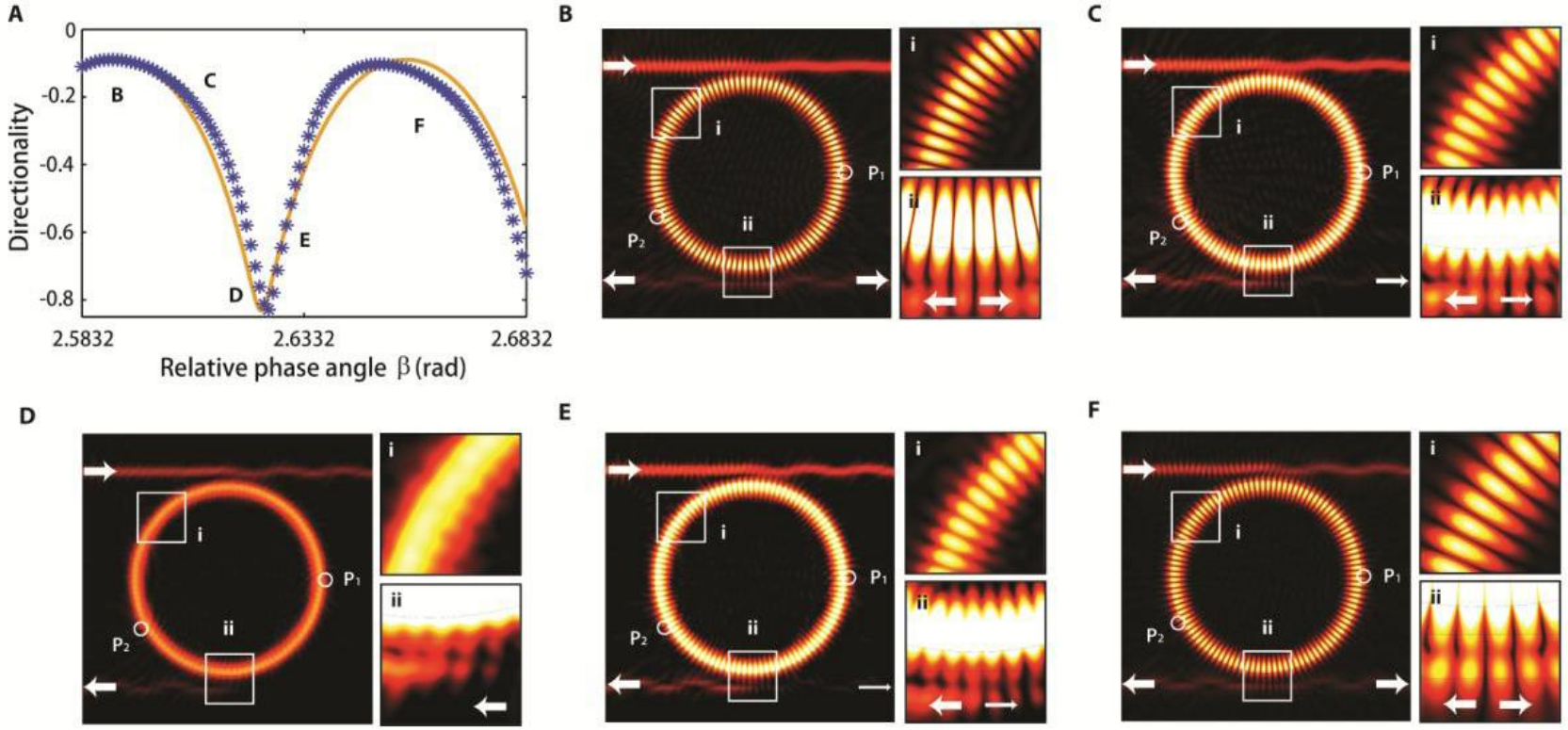




$$D = \frac{I_{bccw} - I_{bcw}}{I_{bccw} + I_{bcw}}$$

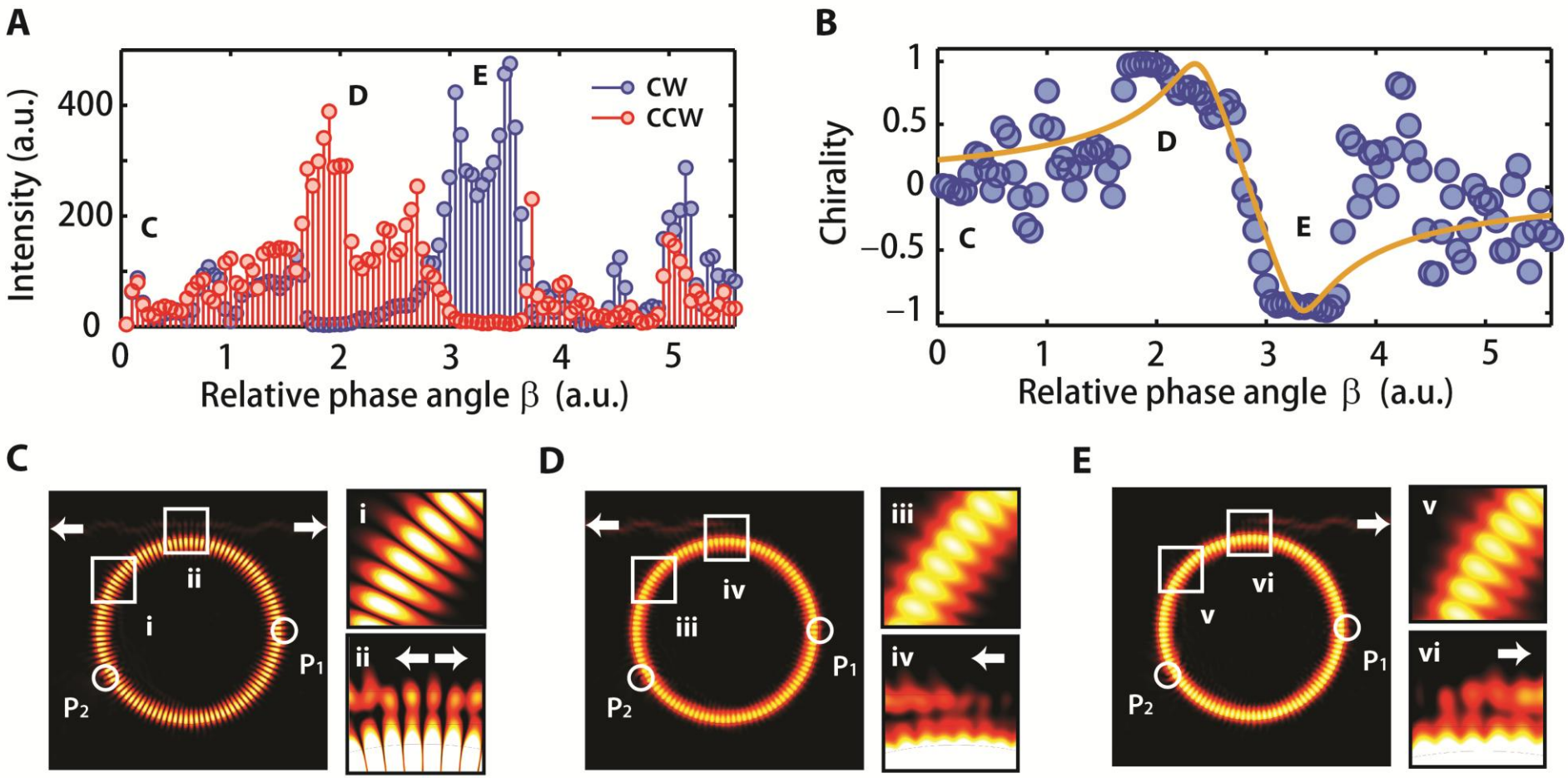
- Decreasing directionality implies scattering into the opposite direction of the input.
- Initial direction (i.e., the direction in which the input light is injected) remained dominant

Directionality: sense of rotation of the cavity light



- Decreasing directionality implies scattering into the opposite direction of the input.
- Initial direction (i.e., the direction in which the input light is injected) remained dominant
- Standing wave: Light couples out in both directions.
- Washed out nodal lines (travelling wave): Light couples out in the direction of the injected light

Controlling lasing direction at an EP



[Peng, Ozdemir, Liertzer, Chen, Kramer, Yilmaz, Wiersig, Rotter and Yang, PNAS 113, 201603318 (2016)]

Agenda

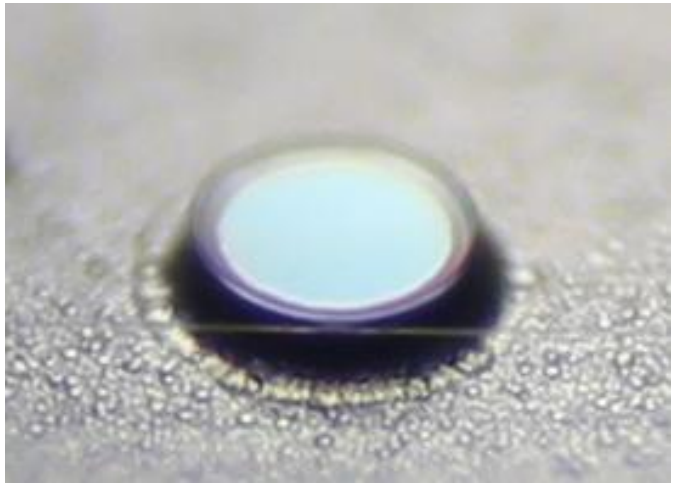
1. PT and EP in optical systems: Brief review
2. Whispering-gallery-mode (WGM) resonators
3. PT-symmetric WGM microresonators
4. Loss-induced suppression and revival of lasing at an EP
5. Chiral modes and directional emission at EPs
6. Conclusions

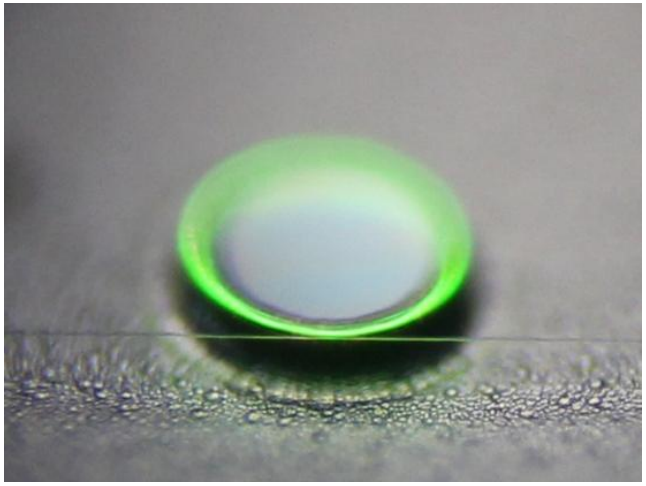
Conclusions

- Exceptional points with WGM microcavities
  - Enhancement of nonlinearities in the vicinity of an EP by introducing loss
  - Loss-induced annihilation and recovery of laser
  - Controlling chirality and lasing directionality
  - Next …….
    - Sensing and metrology at EPs
    - Optomechanics in PT-symmetric systems

Acknowledgement

For more information about our work, please visit
http://ese.wustl.edu/~yang/





NSF

DoD-PECASE