Enhanced sensitivity at higher-order exceptional points

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LETTER

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Enhanced sensitivity at higher-order exceptional points

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- **Plasmonics and Applied Quantum Optics(PAQO) group**

Research interest

- **Metallic nanoscale lasers**
- **Microring semiconductor lasers**
- **Silicon photonic devices**

http://paqo.creol.ucf.edu/

Publication list

2017

"Parity-Time Symmetry in Optics " Encyclopedia of Modern Optics II, Submitted

"Integrated multi-port circulators for unidirectional optical information transport " Scientific Reports 7, Article number: 2129

"Ultrasensitive micro-scale parity-time-symmetric ring laser gyroscope " Optics Letters 42, 1556-1559

"Dynamically Encircling Exceptional Points: Exact Evolution and Polarization State Conversion " Physical Review Letters, 118(9), 093002

2016

"Single mode lasing in transversely multi-moded PT-symmetric microring resonators " Laser & Photonics Reviews 10(3), pp.494-499

"Second-order coherence properties of metallic nanolasers " Optica 3(11), pp.1187-1193

"Passive PT-symmetric metasurfaces with directional field scattering characteristics " IEEE Journal of Selected Topics in Quantum Electronics, 22(5), 5000608

"Dark-state lasers: mode management using exceptional points" Optics Letters 41(13), pp.3049-3052

"Enhanced UV upconversion emission using plasmonic nanocavities " Optics Express 24(13), pp.13999-14009

"Metallic coaxial nanolasers " Advances in Physics: X 1(2), pp.262-275

"Integrable nonlinear parity-time-symmetric optical oscillator " Physical Review E, 9394), 042219

"Design considerations for single mode microring lasers using parity-time-symmetry " IEEE, Journal of Selected Topics in Quantum Electronics

2015

"Nonlinear reversal of the PT-symmetric phase transition in a system of coupled semiconductor microring resonators " Physical Review A 92(6), pp.063807

"Parity-time-symmetric coupled microring lasers operating around an exceptional point " Optics Letters 40(21), pp.4955-4958

"Supersymmetric laser arrays " Physical Review A 92, pp.033818

2014

"Parity-time–symmetric microring lasers " Science 346, 975

"Exceptional points and lasing self-termination in photonic molecules " Physical Review A 90(1)

2012

"Passive and Active Nanophotonics", Advances in Science and Technology, 82, 9

Exceptional point
PT-symmetry
Laser

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Exceptional points for sensing

PHYSICAL REVIEW A **93**, 033809 (2016)

Sensors operating at exceptional points: General theory

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(Received 8 January 2016; published 4 March 2016)

PRL **112,** 203901 (2014) PHYSICAL REVIEW LETTERS week ending 23 MAY 2014

Enhancing the Sensitivity of Frequency and Energy Splitting Detection by Using Exceptional Points: Application to Microcavity Sensors for Single-Particle Detection

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(Received 30 January 2014; published 20 May 2014)

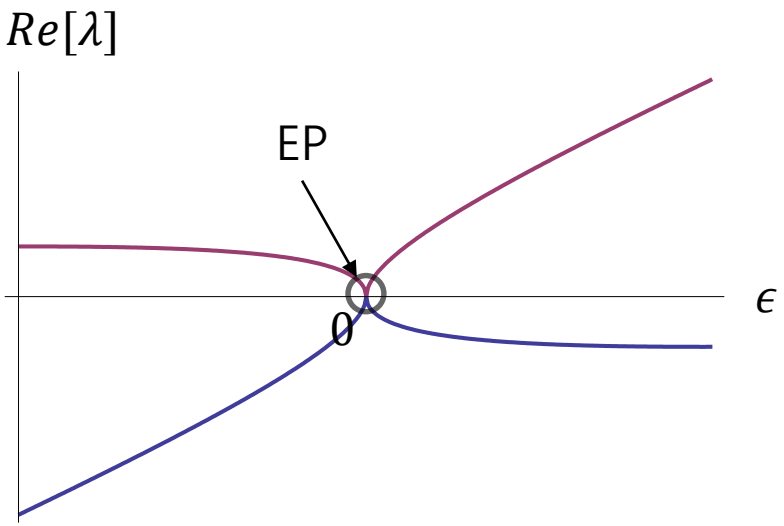
2 x 2 Matrix model

- **PT-symmetric Hamiltonian**

$$\begin{pmatrix} -i\gamma & g \\ g & i\gamma \end{pmatrix}$$

- **Eigenvalues**

$$\lambda = \pm\sqrt{g^2 - \gamma^2}$$



- **Near an EP**

$$\gamma \equiv g$$

$$\begin{pmatrix} \epsilon - ig & g \\ g & ig \end{pmatrix} \quad (\epsilon \ll g)$$

- **Characteristic equation**

$$\lambda^2 - \epsilon\lambda - i\epsilon g = 0$$

$$\Delta\lambda \propto \sqrt{\epsilon}$$

Difference between eigenvalues is very sensitive to perturbations of the parameters!

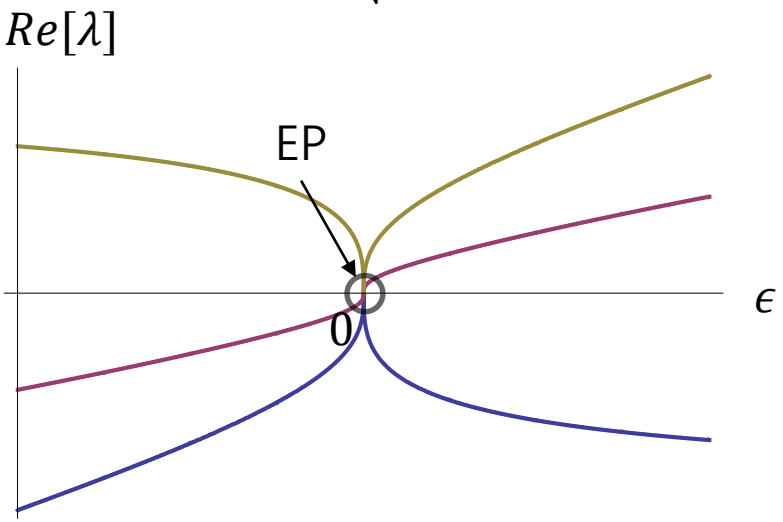
Third-order exceptional points

- **PT-symmetric Hamiltonian**

$$\begin{pmatrix} i\gamma & g & 0 \\ g & 0 & g \\ 0 & g & -i\gamma \end{pmatrix}$$

- **Eigenvalues**

$$\lambda = 0, \pm\sqrt{2}g\sqrt{1-\left(\frac{\gamma}{\sqrt{2}g}\right)^2}$$



- **Near an EP**

$$\gamma \equiv \sqrt{2}g$$

$$\begin{pmatrix} \epsilon + i\sqrt{2}g & g & 0 \\ g & 0 & g \\ 0 & g & -i\sqrt{2}g \end{pmatrix} \quad (\epsilon \ll g)$$

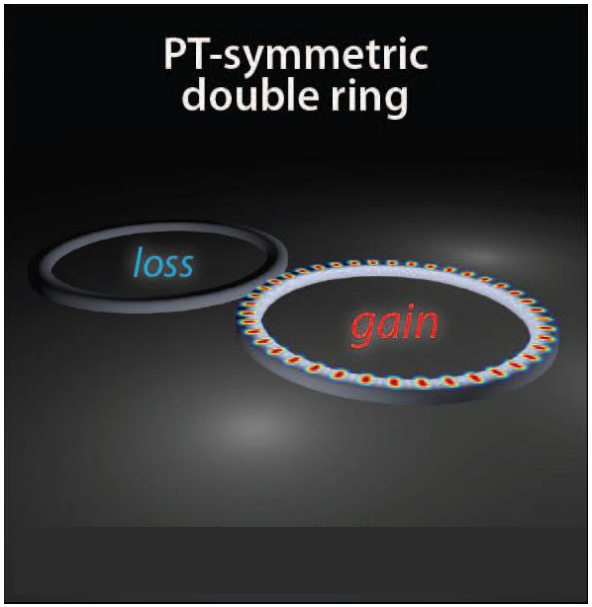
- **Characteristic equation**

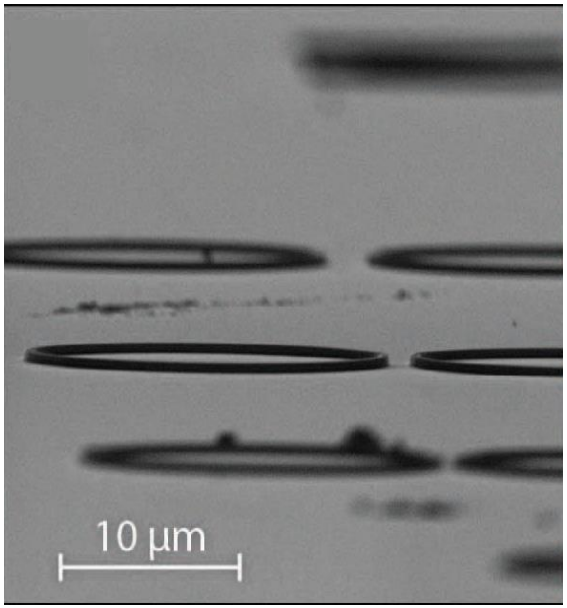
$$\lambda^3 - \epsilon\lambda^2 - i\sqrt{2}\epsilon\lambda g + \epsilon g^2 = 0$$

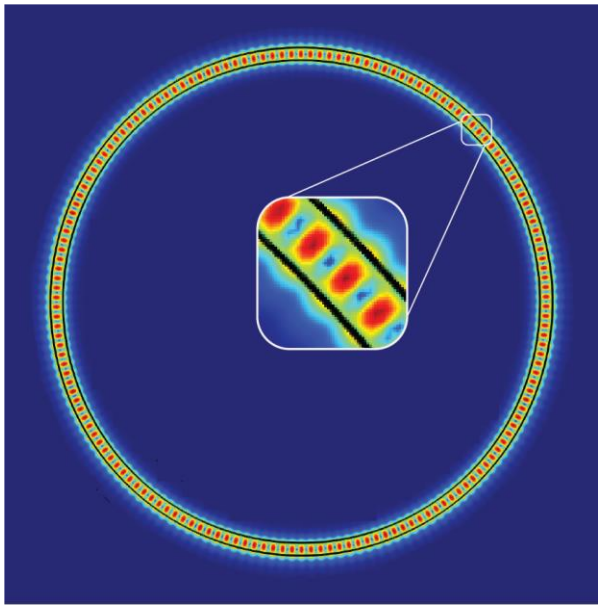
$$\Delta\lambda \propto \epsilon^{\frac{1}{3}}$$

In general, differences between eigenvalues are proportional to $\epsilon^{\frac{1}{N}}$. (N : order of EP)

Microring resonator





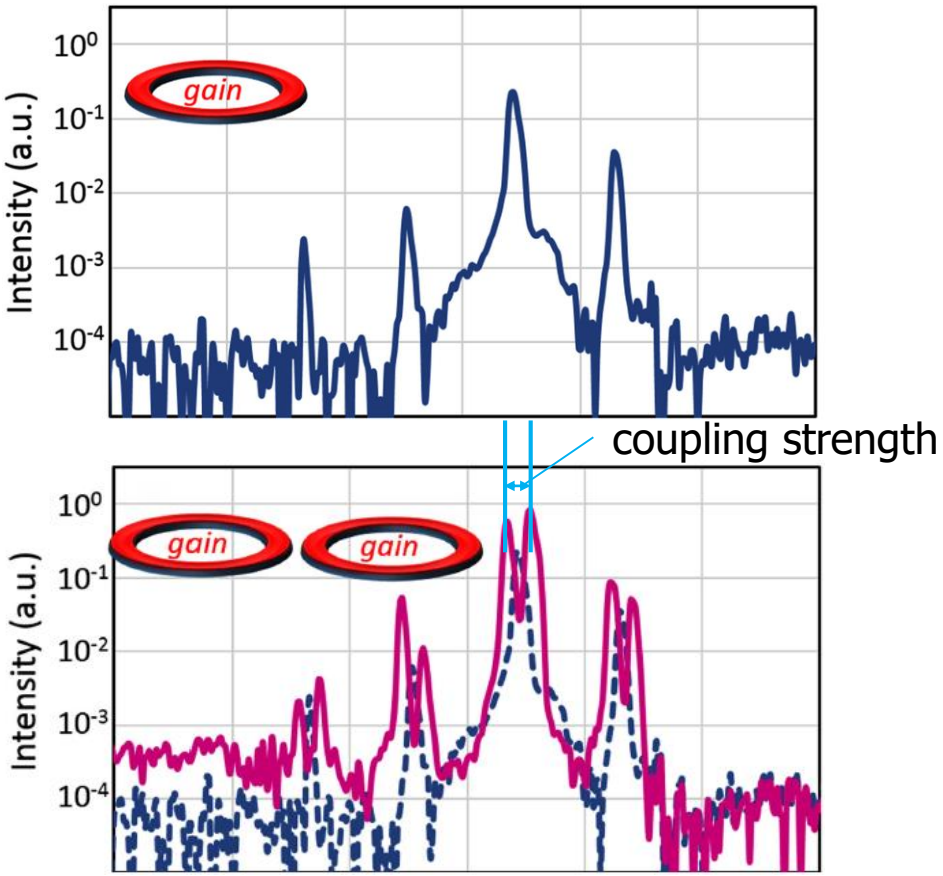


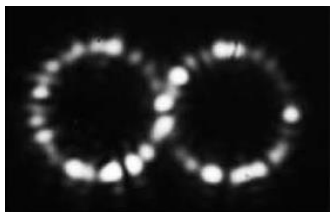
InGaAsP quantum well microrings

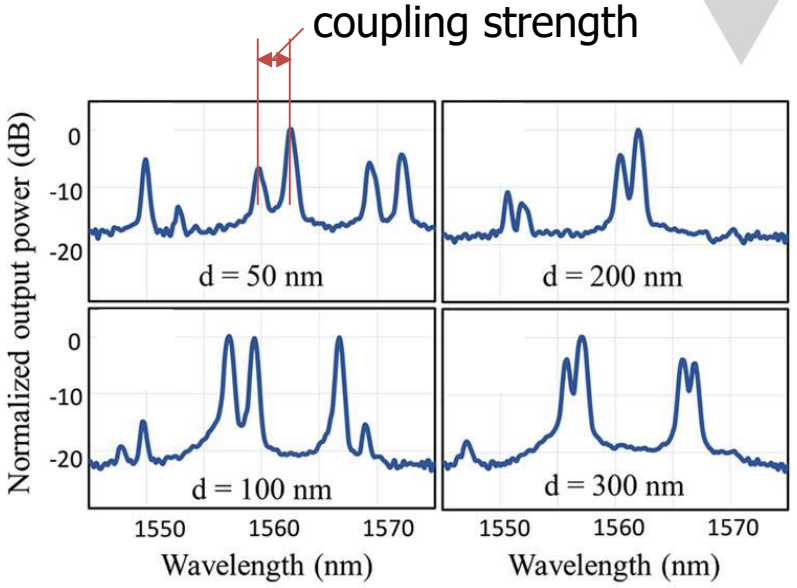
Radius : 10 μm Width: 500 nm Height : 210 nm

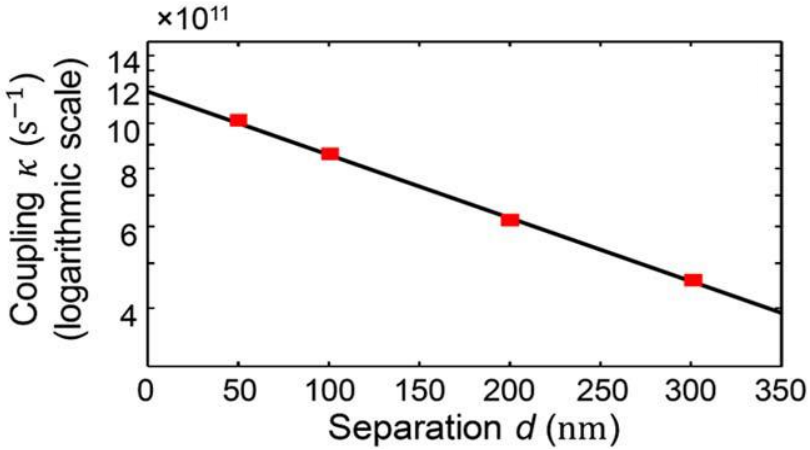
H. Hodaei *et al.*, Science 346, 975 (2014).

Coupling between microrings





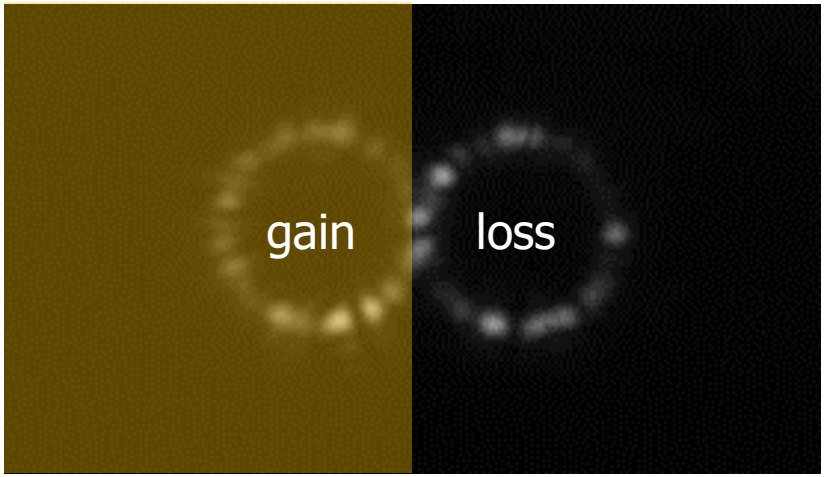


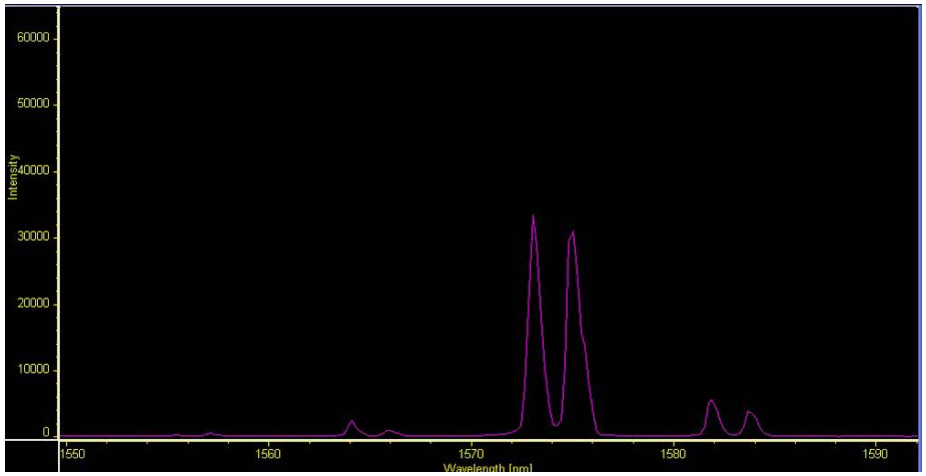


H. Hodaei *et al.*, Opt. Lett. 40, 4955 (2015).

H. Hodaei *et al.*, IEEE J. Sel. Top. Quantum Electron. 22, 1 (2016).

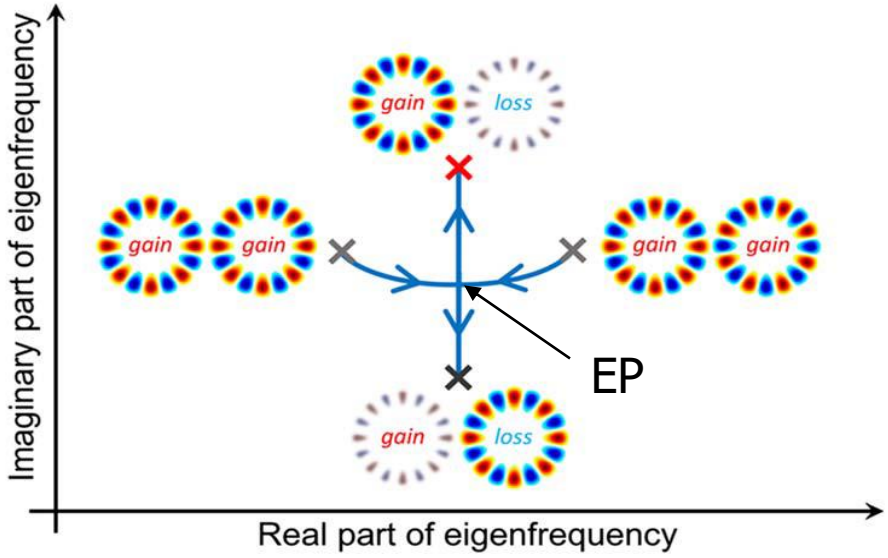
PT-symmetric resonator





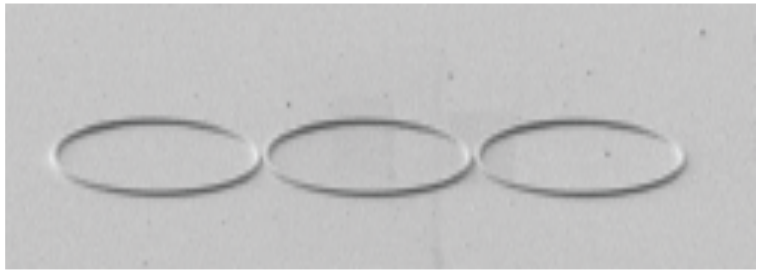
Pump laser on

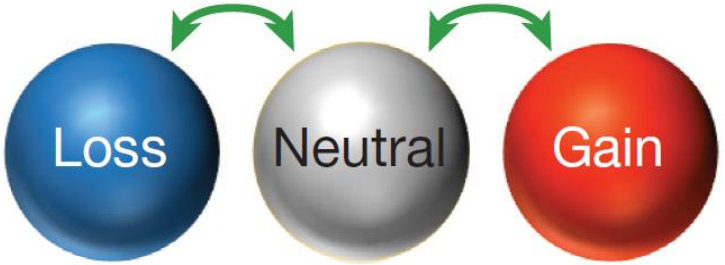
Knife edge sweep

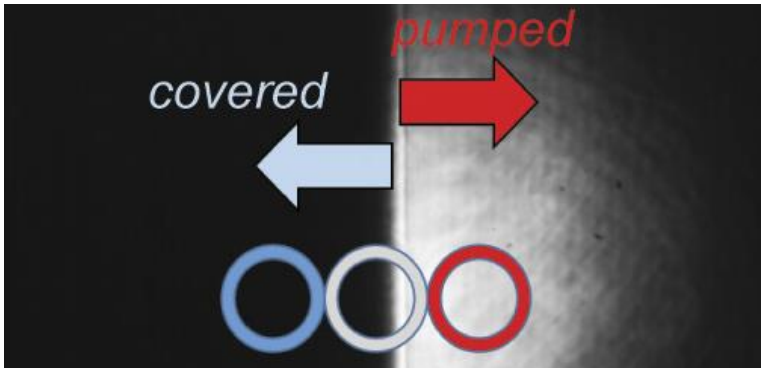


https://figshare.com/articles/Visualization_1_Parity-time-symmetric_coupled_microring_lasers_operating_around_an_exceptional_point/4920311

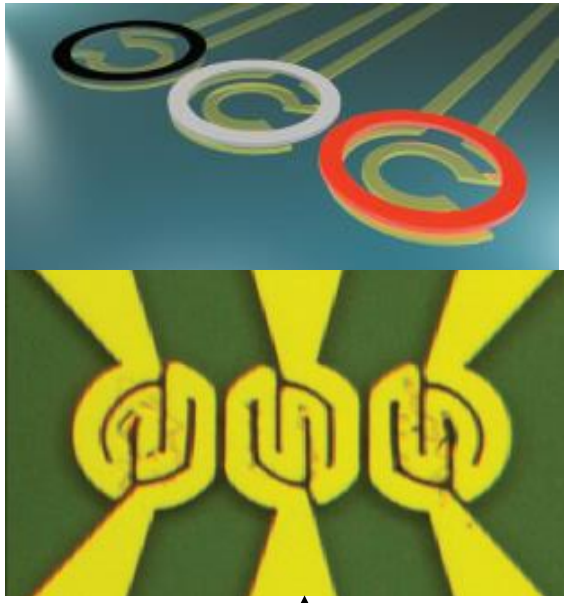
Microrings for Third-order EP

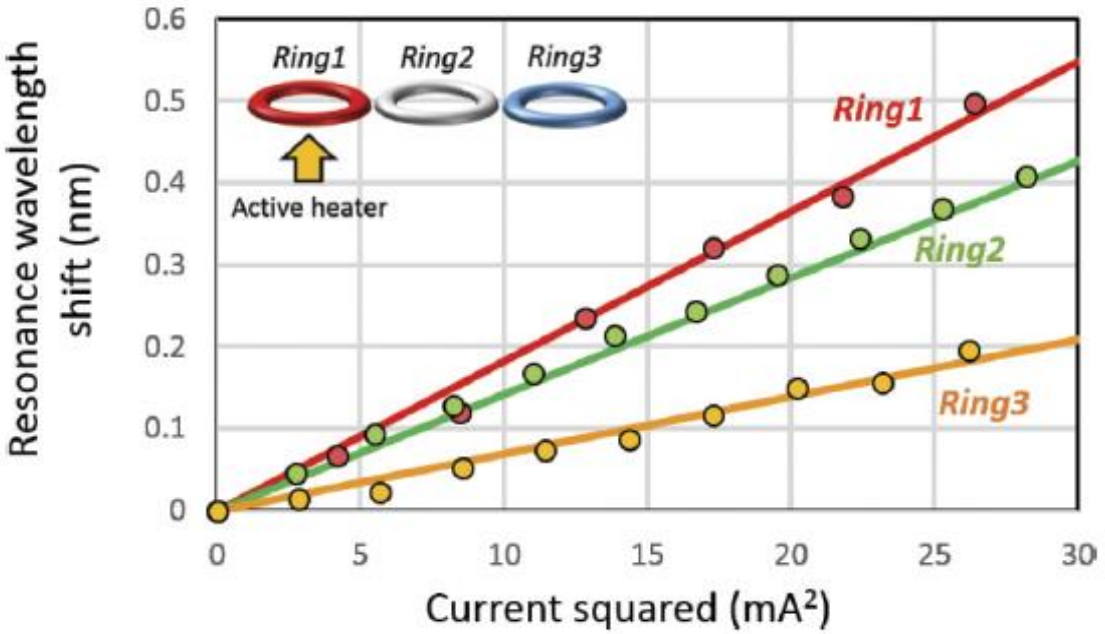






Refractive index perturbations

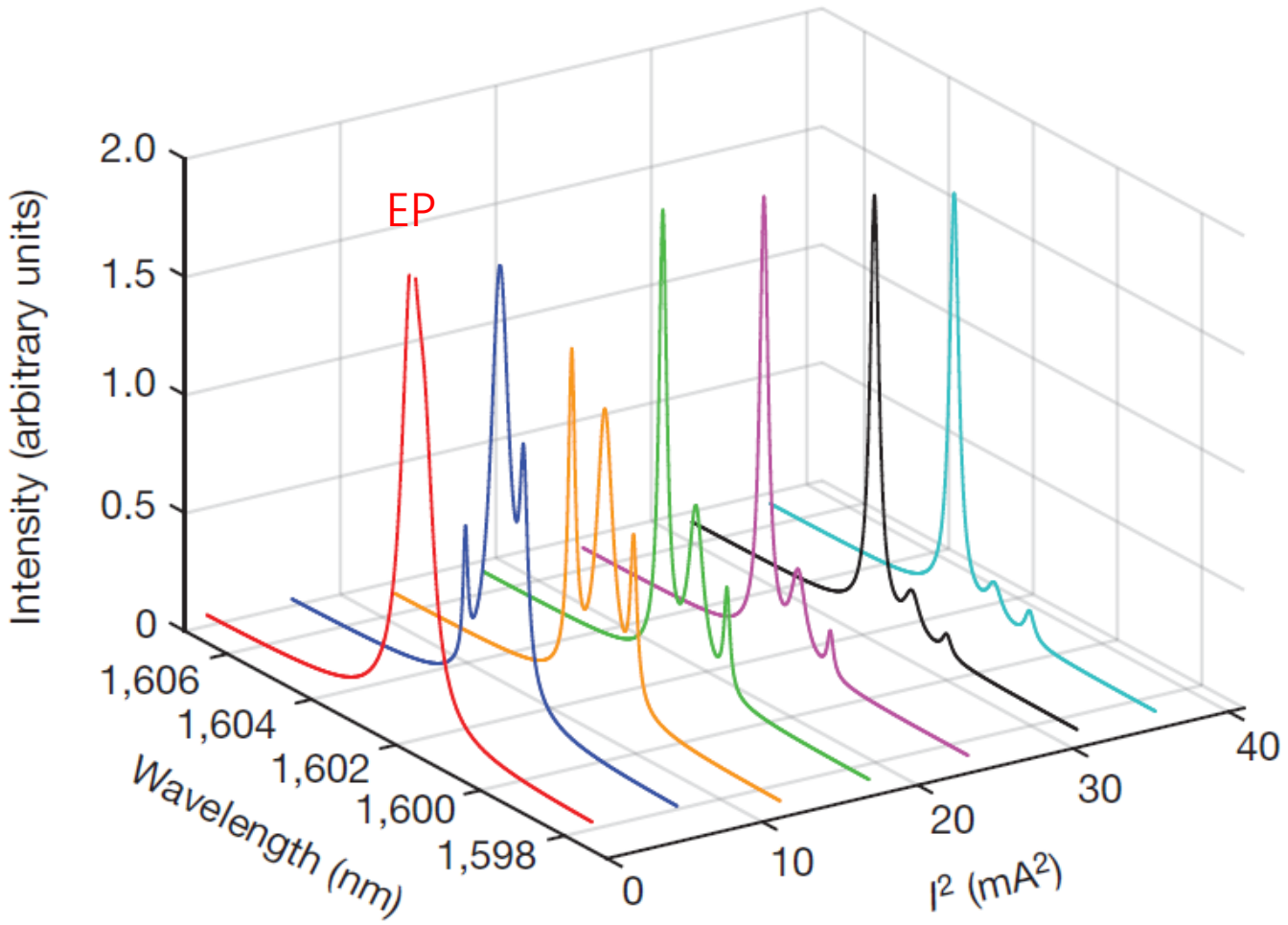




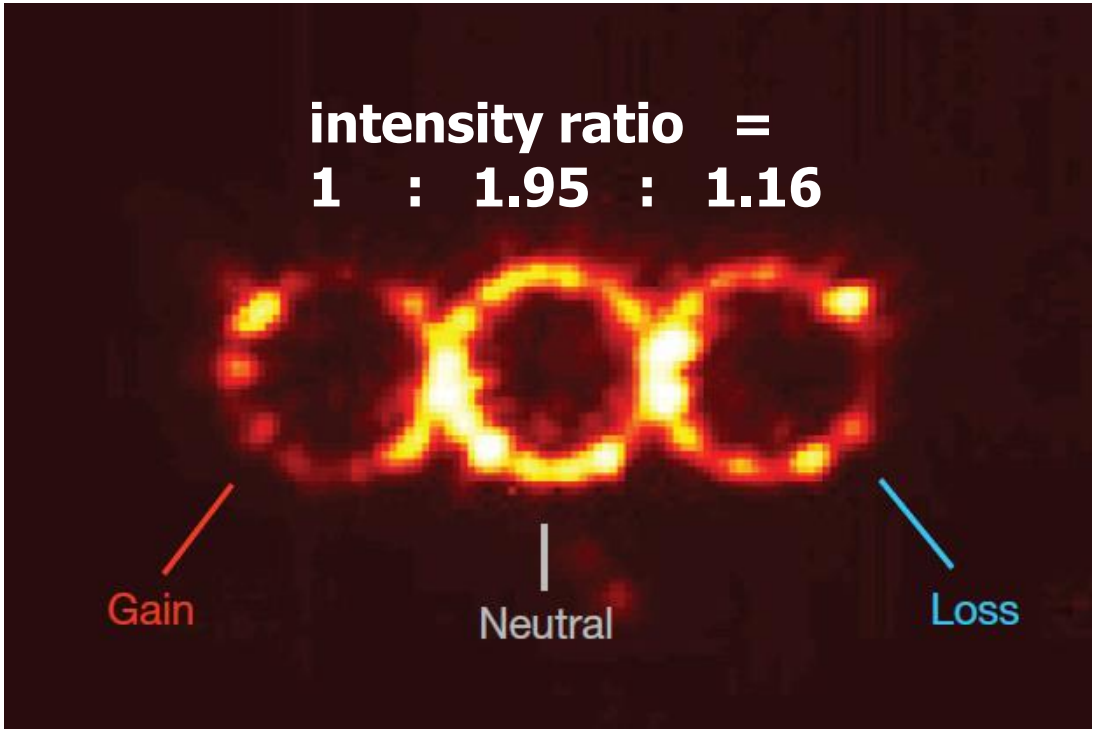
$$\begin{pmatrix} \epsilon_1 + i\sqrt{2}g & g & 0 \\ g & \epsilon_2 & g \\ 0 & g & \epsilon_3 - i\sqrt{2}g \end{pmatrix}$$

Three gold microheaters are fabricated underneath each cavity.

Eigenvalue measurement

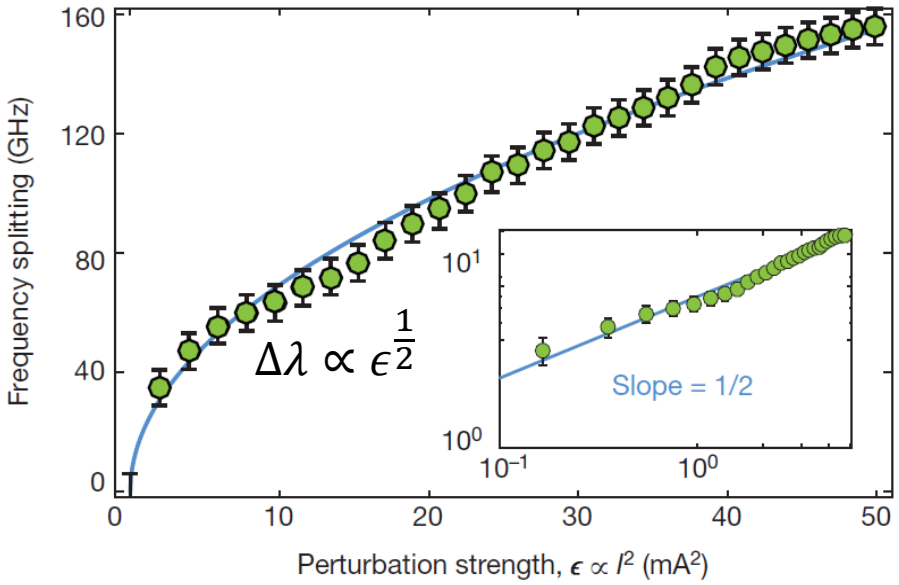


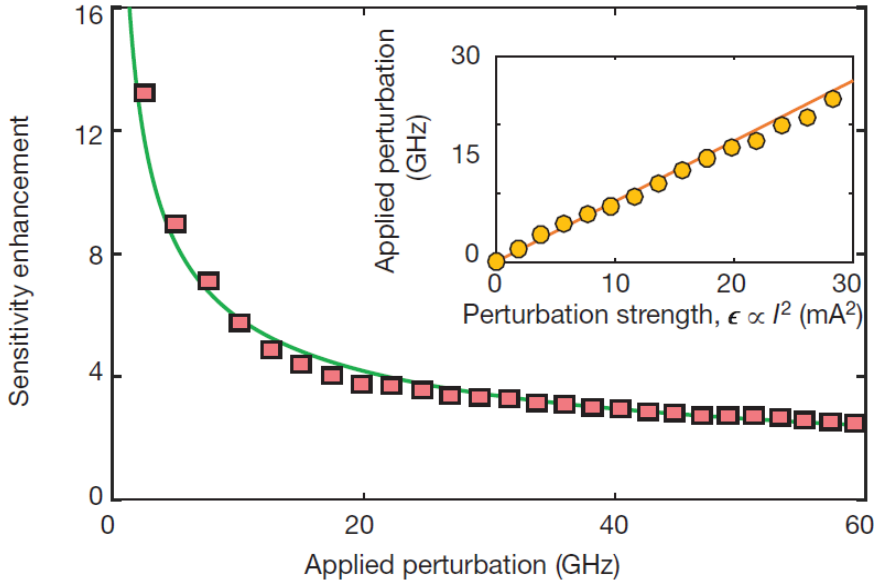
Eigenmode at EP



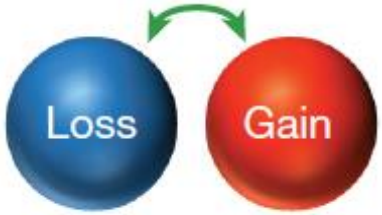
$$\begin{pmatrix} i\sqrt{2}g & g & 0 \\ g & 0 & g \\ 0 & g & -i\sqrt{2}g \end{pmatrix} \quad \rightarrow \quad \text{eigenstate} : \begin{pmatrix} 1 \\ -i\sqrt{2} \\ -1 \end{pmatrix}$$

Second-order EP

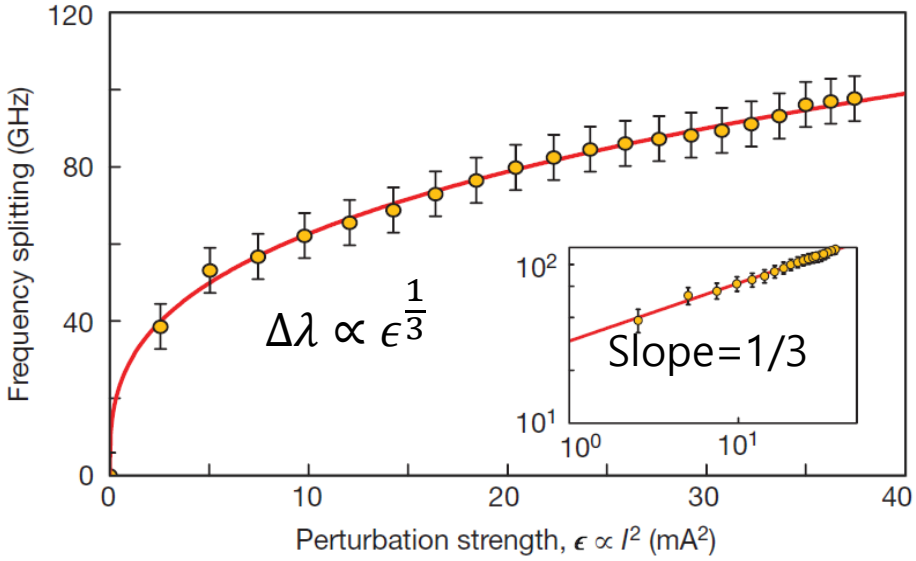


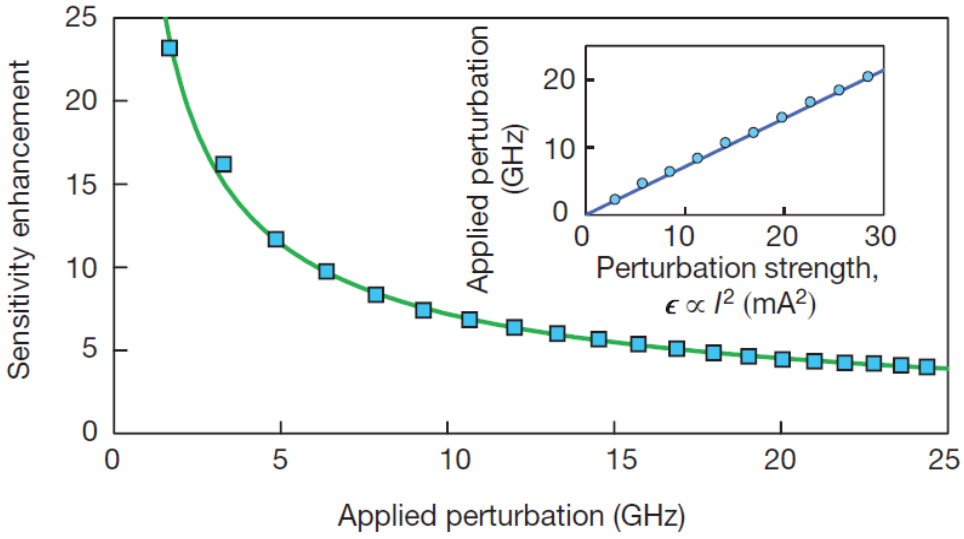


Enhancement factor $\equiv \frac{\Delta\omega}{\epsilon}$

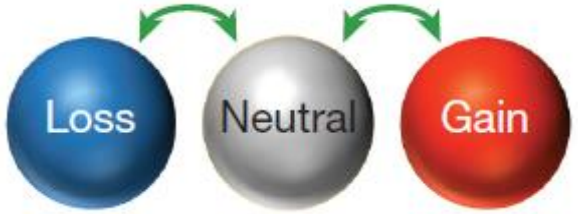


Third-order EP



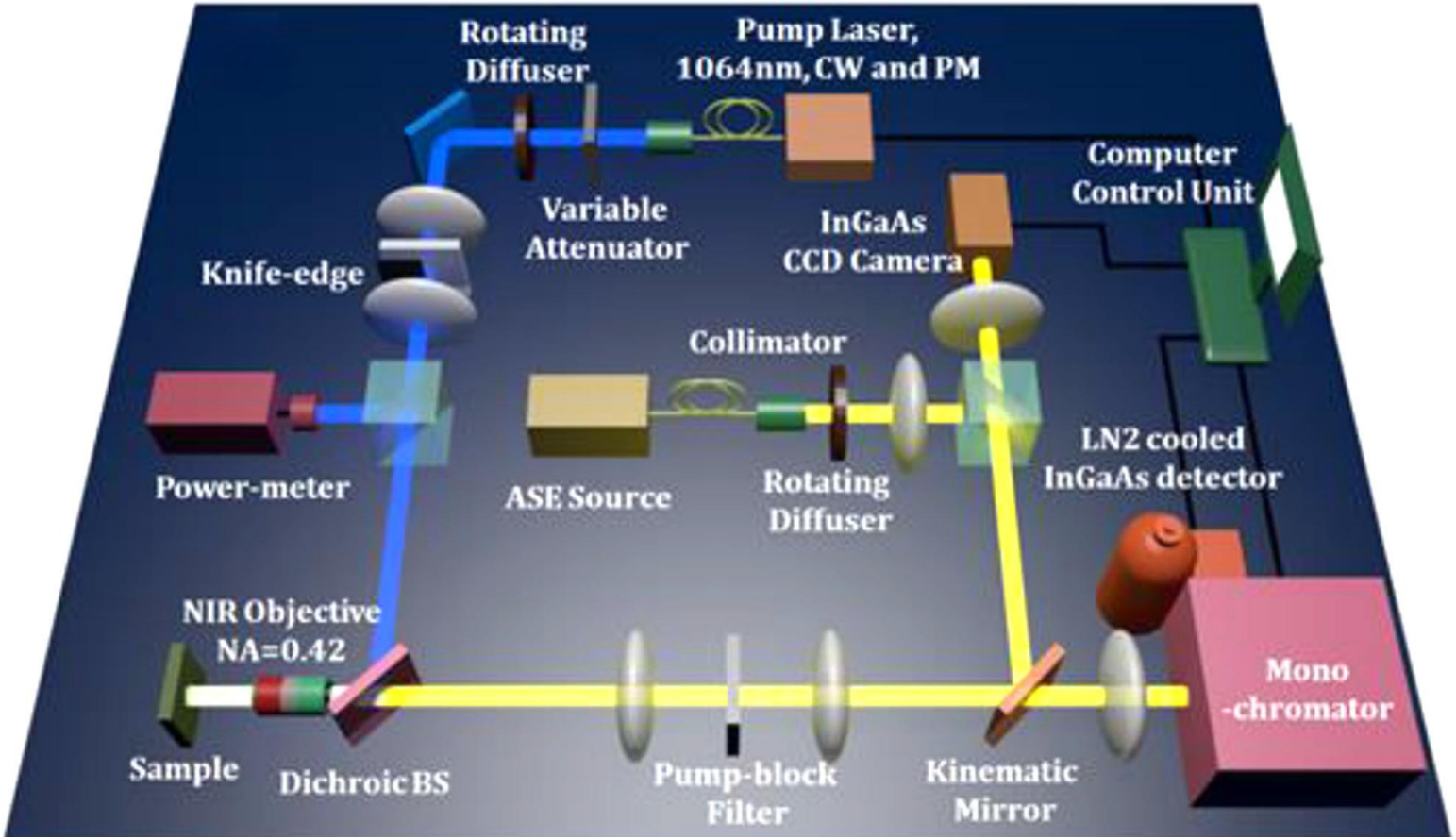


Enhancement factor $\equiv \frac{\Delta\omega}{\epsilon}$



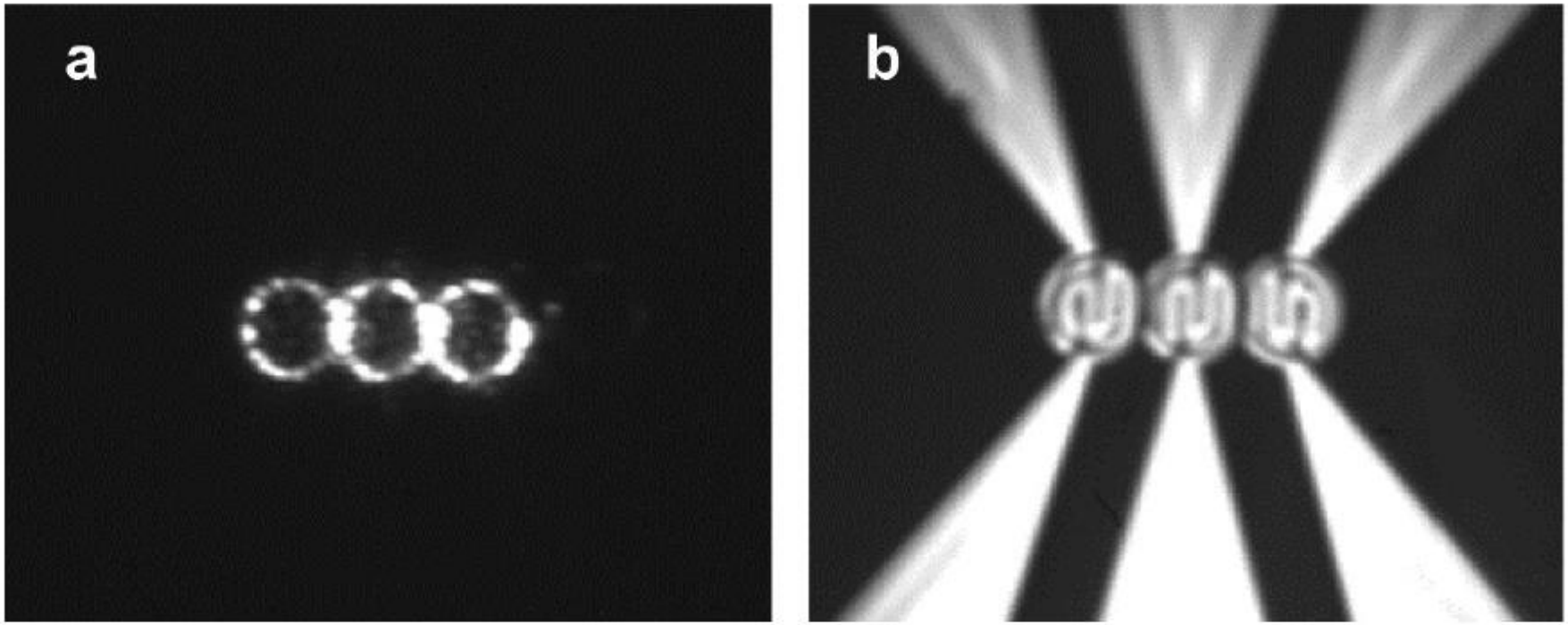
Supplementary Material

Schematic diagram



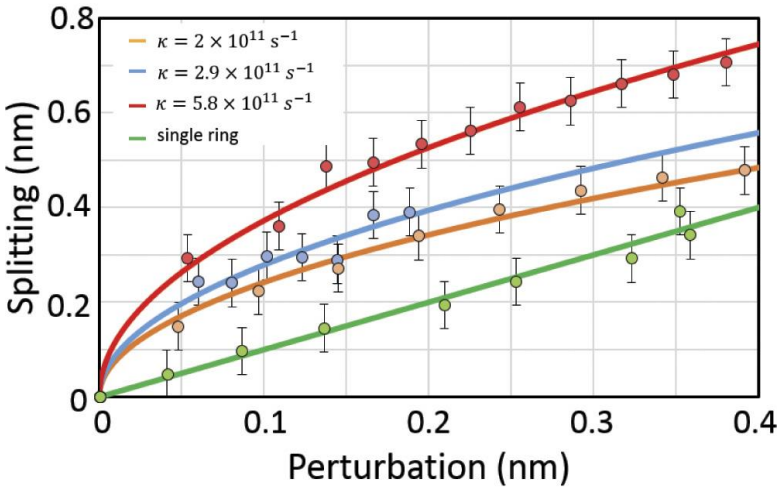
H. Hodaei *et al.*, IEEE J. Sel. Top. Quantum Electron. 22, 1 (2016).

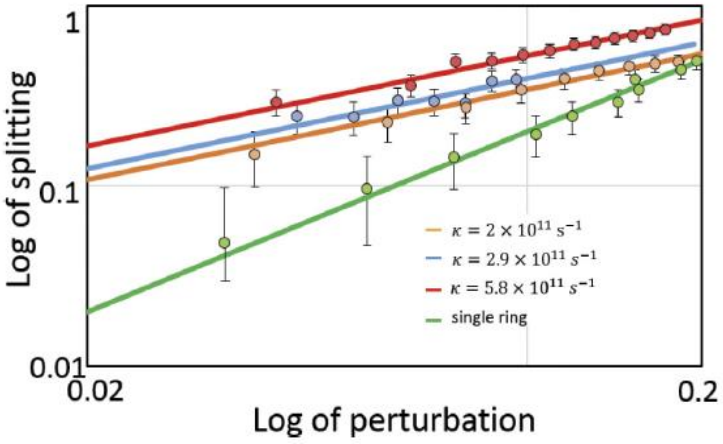
Images of the sample



Extended Data Figure 4 | Sample imaging. a, The intensity profile of three coupled micro-ring resonators when they all pumped equally. **b**, The associated heaters imaged on the measurement station using a broadband near-infrared source.

Effect of coupling





$$\Delta\lambda \propto \sqrt{g\epsilon}$$