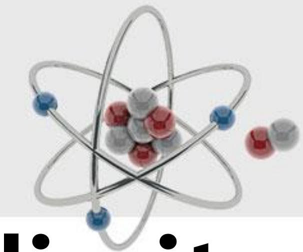


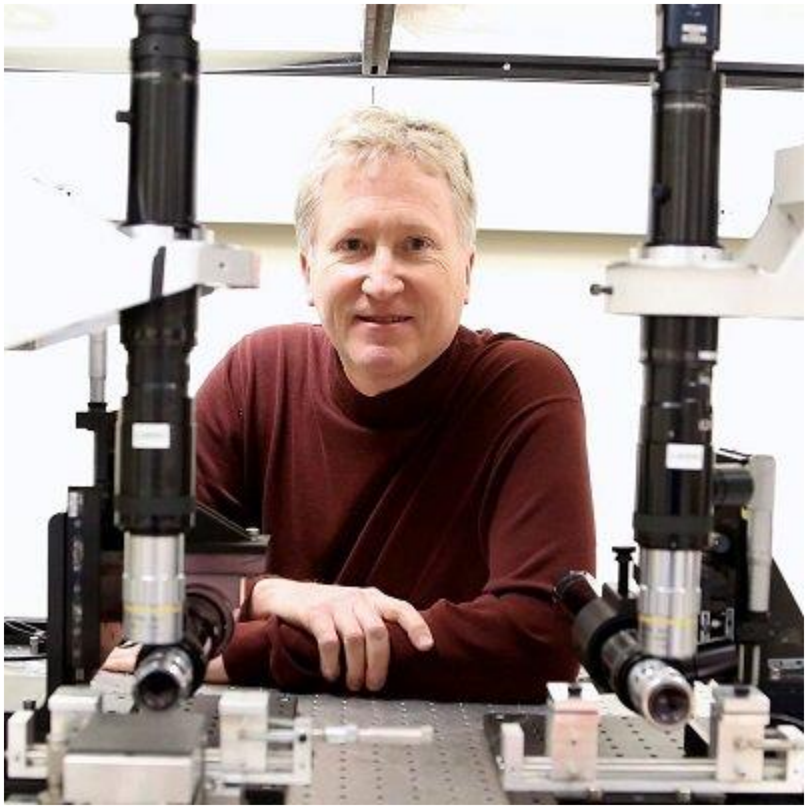
Petermann-factor sensitivity limit near an exceptional point in a Brillouin ring laser gyroscope

Heming Wang, Yu-Hung Lai, Zhiquan Yuan, Myong-Gyun Suh & Kerry Vahala

Nature communications

Published : 31 March 2020

Kerry Vahala



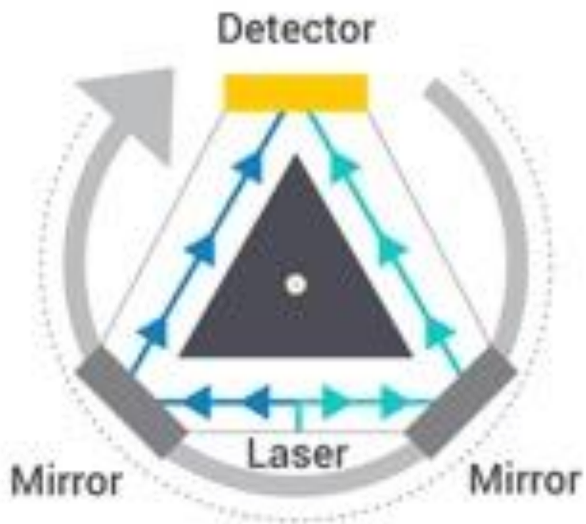
Biography

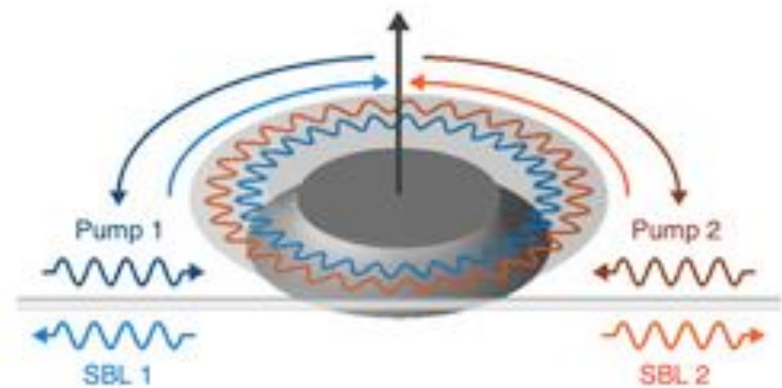
1980: B.S., Caltech.
1981: M.S., Caltech.
1985: Research Fellow in Applied Physics,
1990 - 1996: Assistant Professor.
1996 - 2002: Professor.
2002 - 2013: Jenkins Professor.
2013 - : Executive Officer.

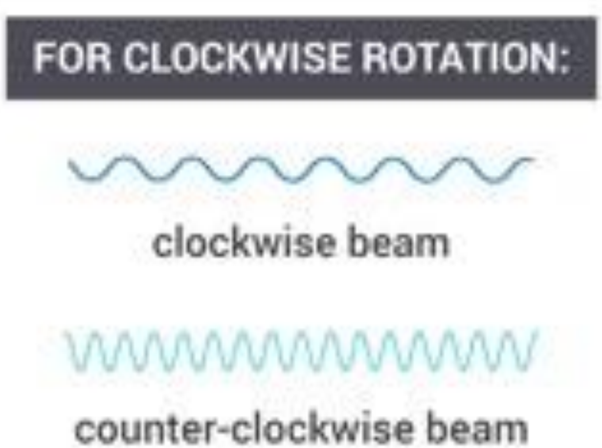
RESEARCH INTERESTS

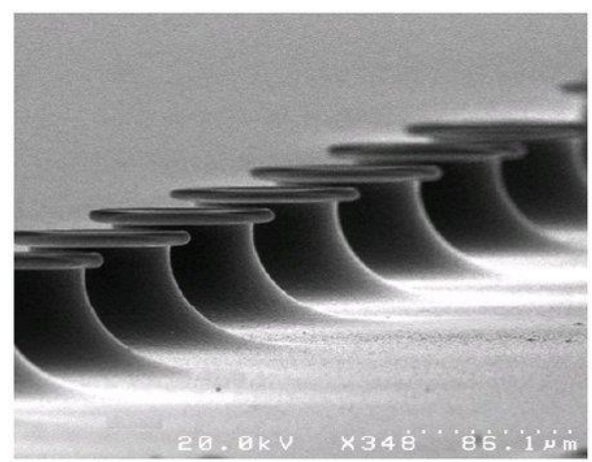
Ultra-High-Q Resonators
Soliton Generation
Microwave Photonics
Cavity Optomechanics
Brillouin Laser

Laser Gyroscope(Sagnac effect)

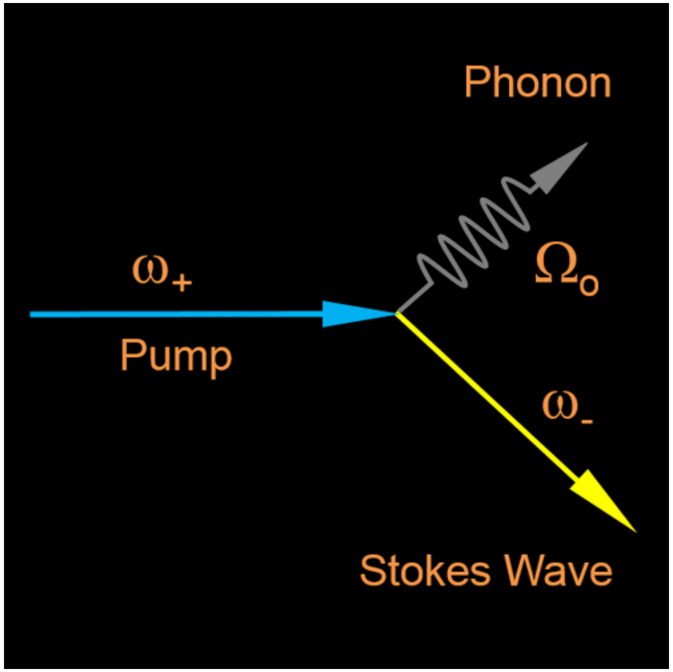


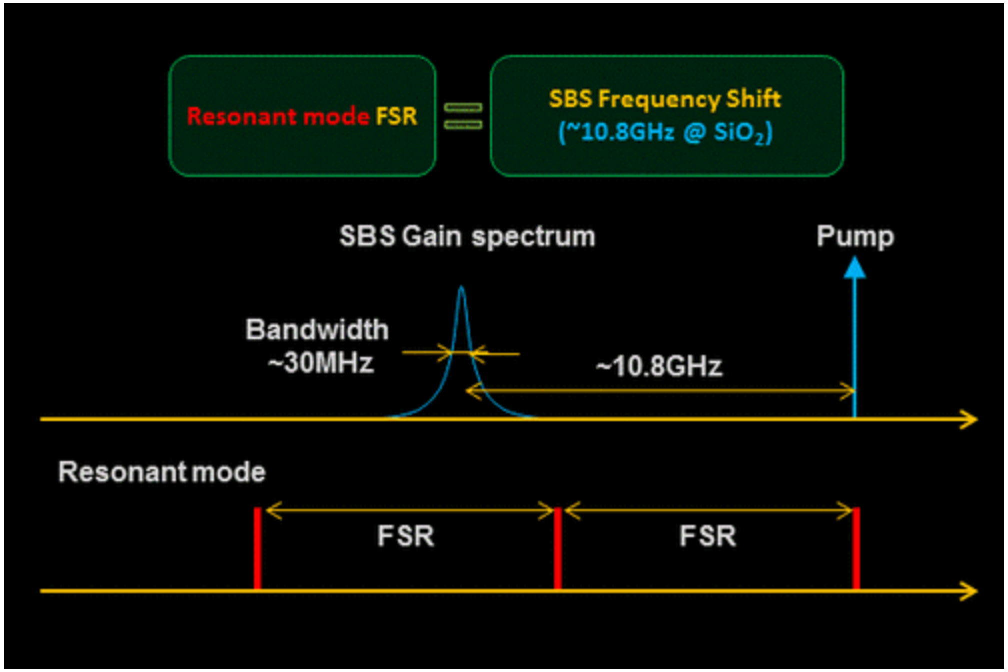




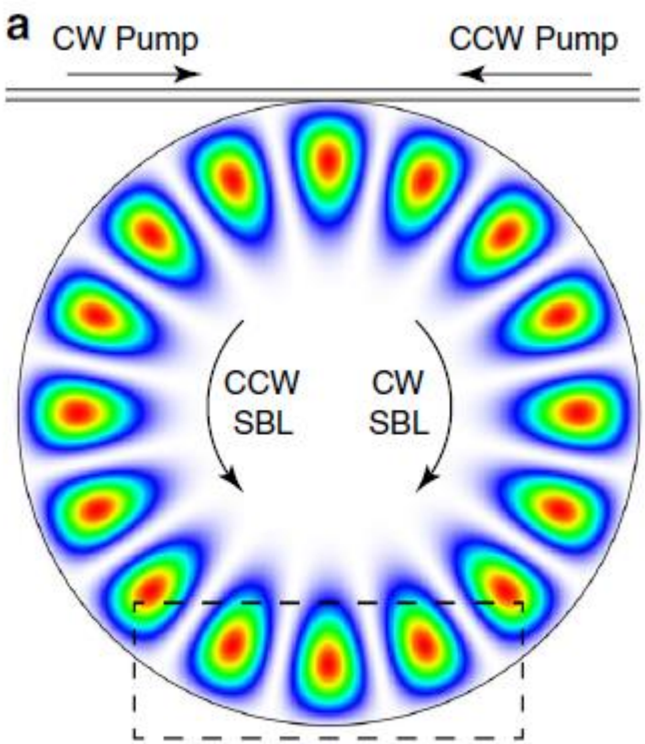


Brillouin Laser





Stimulated Brillouin laser



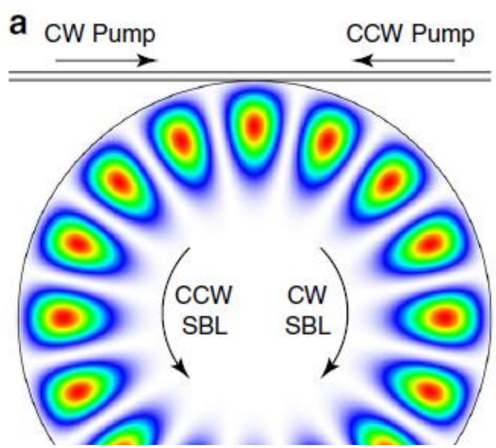
$$H = \begin{pmatrix} \omega_{\mathrm{cw}} & i\Delta\omega_{\mathrm{EP}}/2 \\ i\Delta\omega_{\mathrm{EP}}/2 & \omega_{\mathrm{ccw}} \end{pmatrix}$$

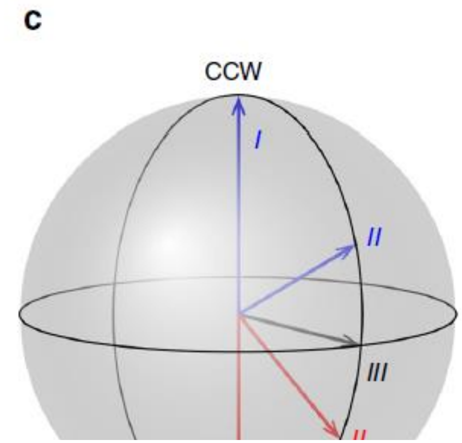
$\Delta\omega_{\mathrm{EP}}$ = Non-Hermition term related to the coupling rate between two SBL modes.

$$\Delta\omega_{\mathrm{S}} = \sqrt{\Delta\omega_{\mathrm{D}}^2 - \Delta\omega_{\mathrm{EP}}^2}$$

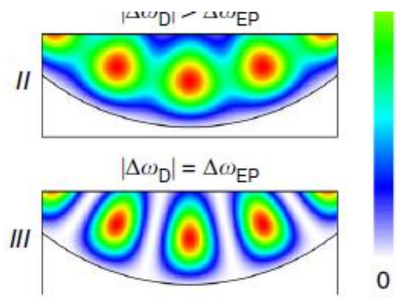
$$(\,\Delta\omega_{\mathrm{D}} \equiv \omega_{\mathrm{ccw}} - \omega_{\mathrm{cw}}\,)$$

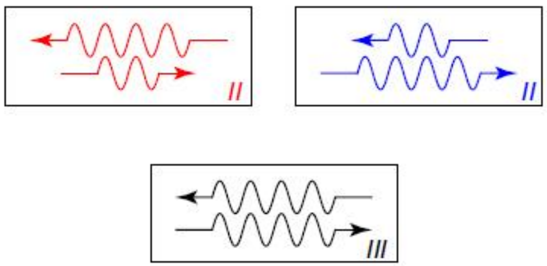
Dependence on the proximity to the exceptional point



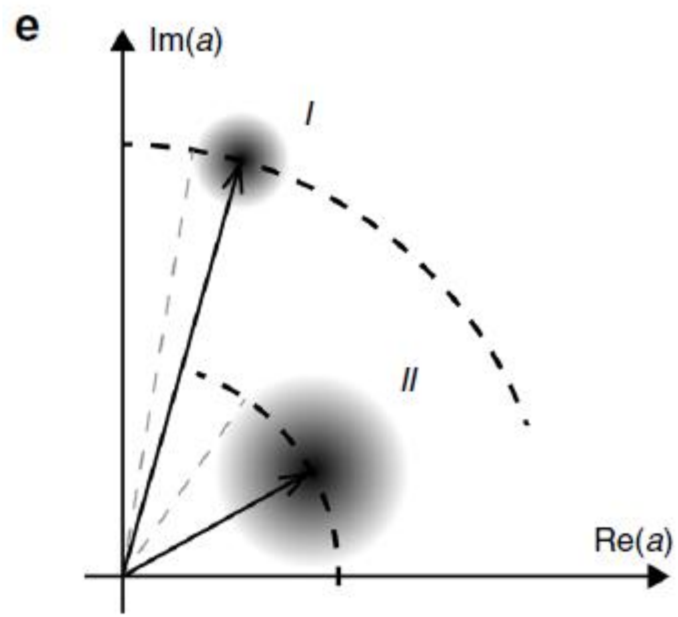


$$\mathrm{SEF} = \left|\frac{\partial \Delta\omega_{\mathrm{S}}}{\partial \Delta\omega_{\mathrm{D}}}\right|^2 = \frac{\Delta\omega_{\mathrm{D}}^2}{\Delta\omega_{\mathrm{D}}^2 - \Delta\omega_{\mathrm{EP}}^2}$$





Linewidth broadening

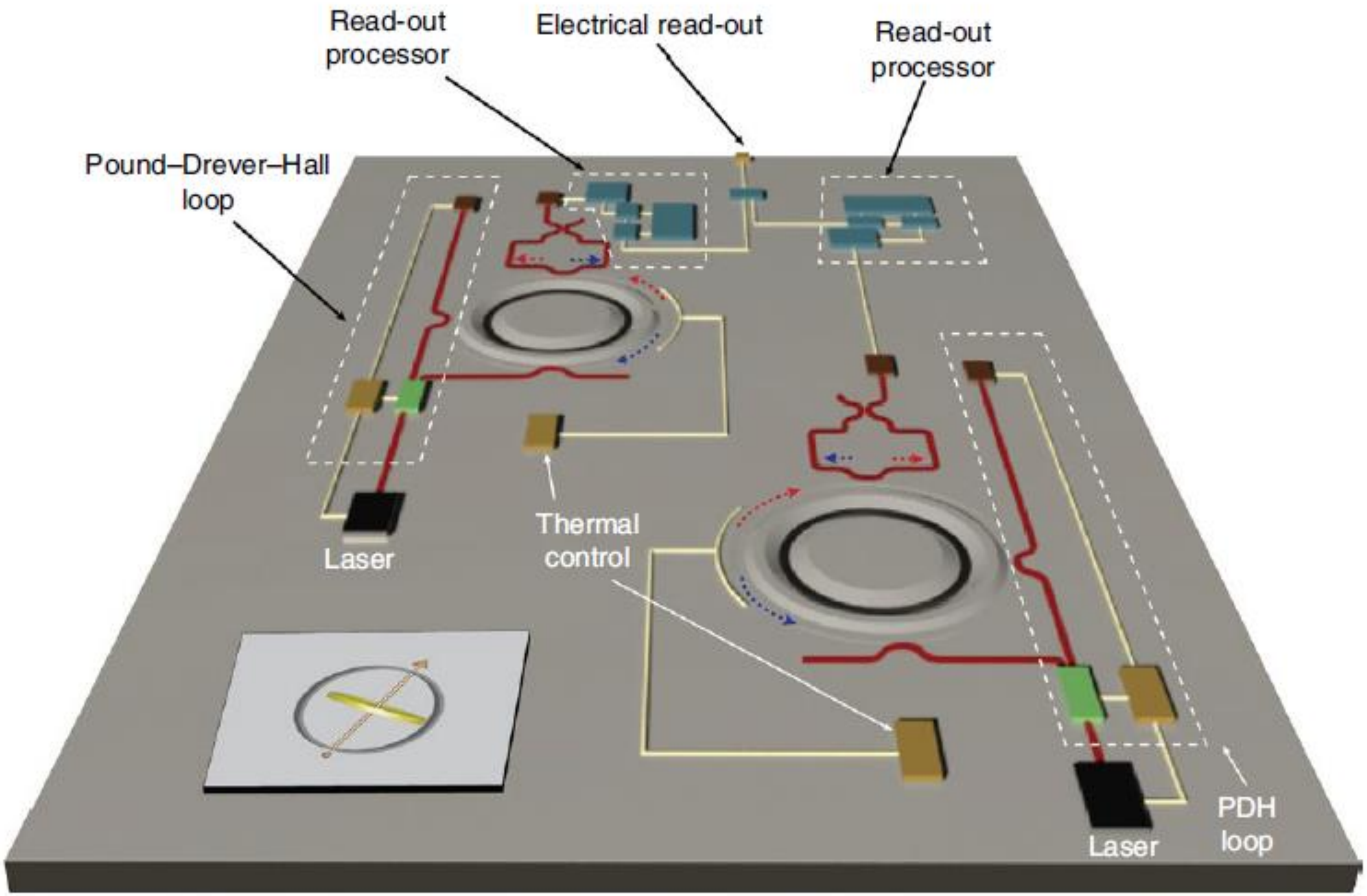


Complex amplitude phasor representation of lasing mode.

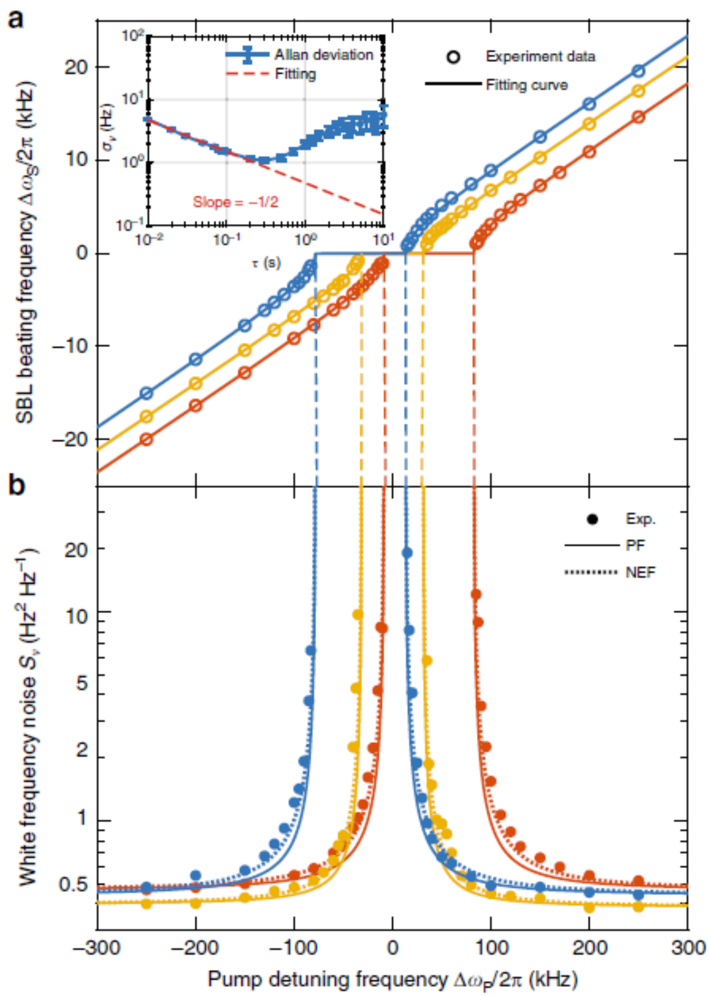
$$\mathrm{PF} = \frac{1}{2}\left(1 + \frac{\mathrm{Tr}(H_0^\dagger H_0)}{|\mathrm{Tr}(H_0^2)|}\right) = \frac{\Delta\omega_\mathrm{D}^2}{\Delta\omega_\mathrm{D}^2 - \Delta\omega_\mathrm{EP}^2}$$

$$\mathrm{SEF} = \left|\frac{\partial\Delta\omega_\mathrm{S}}{\partial\Delta\omega_\mathrm{D}}\right|^2 = \frac{\Delta\omega_\mathrm{D}^2}{\Delta\omega_\mathrm{D}^2 - \Delta\omega_\mathrm{EP}^2}$$

Experimental setup



Linewidth enhancement near the exceptional point



$$\Delta\omega_S = \pm\sqrt{\Delta\omega_D^2 - \Delta\omega_{EP}^2}$$

$$\left(\Delta\omega_D = \frac{\gamma/\Gamma}{1+\gamma/\Gamma}\Delta\omega_P + \frac{1}{1+\gamma/\Gamma}\Delta\omega_{Kerr}\right)$$

γ= photon decay rate

Γ= Brillouin gain bandwidth

$\Delta\omega_{kerr}$=Kerr effect correction

Measured SBL beating frequency is plotted versus pump detuning for three distinct locking zones.

Conclusion

Near the exceptional point,

Enhanced transduction of rotation to signal

$$\mathrm{SEF} = \left|\frac{\partial \Delta\omega_{\mathrm{S}}}{\partial \Delta\omega_{\mathrm{D}}}\right|^2 = \frac{\Delta\omega_{\mathrm{D}}^2}{\Delta\omega_{\mathrm{D}}^2 - \Delta\omega_{\mathrm{EP}}^2}$$

⟺

Enhanced noise by bi-orthogonality

$$\mathrm{PF} = \frac{1}{2}\left(1 + \frac{\mathrm{Tr}(H_0^\dagger H_0)}{|\mathrm{Tr}(H_0^2)|}\right) = \frac{\Delta\omega_{\mathrm{D}}^2}{\Delta\omega_{\mathrm{D}}^2 - \Delta\omega_{\mathrm{EP}}^2}$$

Improved responsivity does not lead to an improvement of sensitivity.

LETTER

doi:10.1038/nature23281

Exceptional points enhance sensing in an optical microcavity

Weijian Chen[1], Şahin Kaya Özdemir[1], Guangming Zhao[1], Jan Wiersig[2] & Lan Yang[1]

Sensors play an important part in many aspects of daily life such as infrared sensors in home security systems, particle sensors for environmental monitoring and motion sensors in mobile phones. High-quality optical microcavities are prime candidates for sensing applications because of their ability to enhance light–matter interactions in a very confined volume. Examples of such devices include mechanical transducers[1], magnetometers[2], single-particle absorption spectrometers[3], and microcavity sensors for sizing single particles[4] and detecting nanometre-scale objects such as single nanoparticles and atomic ions[5–7]. Traditionally, a very small perturbation near an optical microcavity introduces either a change in the linewidth or a frequency shift or splitting of a resonance that is proportional to the strength of the perturbation. Here we demonstrate an alternative sensing scheme, by which the sensitivity of microcavities can be enhanced when operated at non-Hermitian spectral degeneracies known as exceptional points[8–16]. In our experiments, we use two nanoscale scatterers to tune a whispering-gallery-mode micro-toroid cavity, in which light propagates along a concave surface by continuous total internal reflection, in a precise and controlled manner to exceptional points[12,13]. A target nanoscale object that subsequently enters the evanescent field of the cavity perturbs the system from its exceptional point, leading to frequency splitting.

One key difference between exceptional points and conventional degeneracies known as diabolic points is their sensitivity to perturbations. In a system operating around a diabolic point, the resulting eigenvalue splitting is proportional to the perturbation strength ϵ. In contrast, for a system with an Nth-order exceptional point, at which N eigenvalues and the corresponding eigenvectors coalesce, the splitting induced by the perturbation scales as $\epsilon^{1/N}$. Hence, for a sufficiently small perturbation ϵ, the splitting at the exceptional point is larger. This particular characteristic of exceptional points has been proposed for use in sensor applications[25–27].

Here we experimentally demonstrate such an exceptional-point sensor, highlighting the enhancement of the sensitivity. Our system[12,13] consists of a silicon dioxide (silica) micro-toroid cavity coupled to a fibre-taper waveguide for in- and out-coupling of light (Extended Data Fig. 1). With its circular geometry, the micro-toroid cavity supports clockwise- and anticlockwise-travelling modes with degenerate eigenfrequencies but orthogonal eigenvectors—that is, the cavity operates at a diabolic point. To set up an exceptional-point sensor, we use two silica nano-tips as Rayleigh scatterers within the mode volume of the cavity to tune the coupling between clockwise- and anticlockwise-travelling modes to steer the system to an exceptional point. In the experiments, we first located an optical resonance mode with no observable mode