# Two ways to improve optical sensing using different resonator techniques

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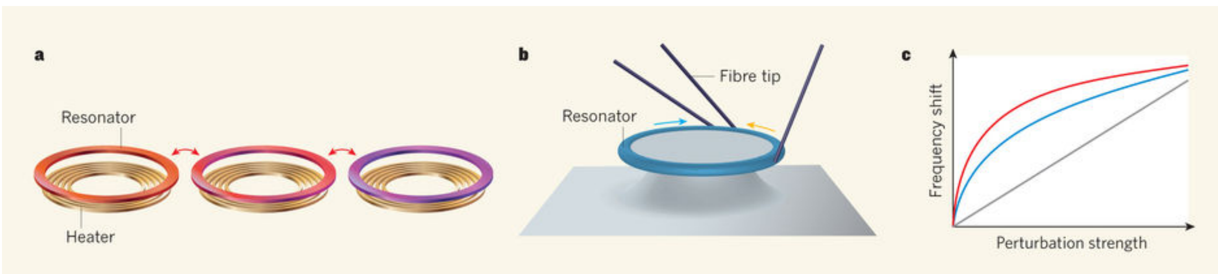


Structures called optical resonators trap light at certain frequencies. When the environment of such a resonator is perturbed, these frequencies shift, which allows optical resonators to be used as sensors. a, Hodaei et al. report a sensor that consists of three ring-shaped resonators that are coupled (red arrows). The authors use gold heating elements both to precisely tune the sensor and to emulate perturbations. b, By contrast, Chen et al. use a single toroidal resonator, and couple light that travels in clockwise (blue arrow) and anticlockwise (yellow arrow) directions. The authors use two fibre tips to tune the sensor and another type of tip to introduce perturbations. c, In conventional sensors, the shift in frequency caused by a perturbation is directly proportional to the strength of the perturbation (grey line). Hodaei et al. and Chen et al. demonstrate that the frequency shift in their sensing devices scales with the cube root (red line) or square root (blue line) of the perturbation strength, respectively. This leads to a dramatic improvement in the scaling of sensitivity of such sensors in comparison to conventional devices. Credit: Mikael C. Rechtsman, *Nature* 548, 161–162 (10 August 2017) doi:10.1038/548161a

(Phys.org)—Two independent teams working on research aimed at improving optical sensing have used techniques that involve coupling two or more modes of light such that their modes and their corresponding frequencies coalesce, resulting in more sensitivity. In the first effort, a team from Washington University in St. Lois and Otto-von-Guericke University Magdeburg, in Germany, connected three traditional sensors for more precise tuning. In the second effort, a team from the University of Central Florida and Michigan Technological University used just one resonator but coupled light traveling in both directions around it. Both teams have published papers describing their efforts and results in the journal *Nature*. Mikael Rechtsman with the Pennsylvania State University offers a News & Views piece outlining optical sensing techniques and the work done by the two teams in the same journal issue.

As Rechtsman notes, optical sensors are used in a variety of applications that involve very slight mechanical vibrations or changes in temperature. They are also used when working with nanoparticles or in the analysis of biomolecules. All such sensors have a single problem, however—their performance is limited by the strength of the perturbations under study. In this new effort, both research teams sought to overcome this limitation by coupling modes of light, allowing them to coalesce—this occurs in places called "exceptional points," and they only arise in what are known as Hermitian systems. In such systems, prior research has shown, photon loss is a main feature, as opposed to conventional systems in which the opposite is true. In either case, the result is increased sensitivity, which, of course, translates to more precision.

In the first effort, the researchers connected three ring-shaped sensors together and then added gold heating elements beneath them to fine tune the sensors and to emulate perturbations. In the second effort, the researchers used just one ring-shaped sensor but sent light around it in both directions (both clockwise and counterclockwise) at the same time to cause coalescence. Then, they used a fiber tip to fine tune the sensor and a second tip to cause perturbations.

Both techniques come with a trade-off, Rechtsman notes, between fine-tuning and sensitivity, and there remains the question of whether either or both can be modified to achieve even higher sensitivities.

**More information:** 1. Weijian Chen et al. Exceptional points enhance sensing in an optical microcavity, *Nature* (2017). DOI: 10.1038/nature23281

**Abstract**
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, magnetometers, single-particle absorption spectrometers3, and microcavity sensors for sizing single particles and detecting nanometre-scale objects such as single nanoparticles and atomic ions. 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. 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. A target nanoscale object that subsequently enters the evanescent field of the cavity perturbs the system from its exceptional point, leading to frequency splitting. Owing to the

complex-square-root topology near an exceptional point, this frequency splitting scales as the square root of the perturbation strength and is therefore larger (for sufficiently small perturbations) than the splitting observed in traditional non-exceptional-point sensing schemes. Our demonstration of exceptional-point-enhanced sensitivity paves the way for sensors with unprecedented sensitivity.

2. Hossein Hodaei et al. Enhanced sensitivity at higher-order exceptional points, *Nature* (2017). DOI: 10.1038/nature23280

**Abstract**

Non-Hermitian degeneracies, also known as exceptional points, have recently emerged as a new way to engineer the response of open physical systems, that is, those that interact with the environment. They correspond to points in parameter space at which the eigenvalues of the underlying system and the corresponding eigenvectors simultaneously coalesce1, 2, 3. In optics, the abrupt nature of the phase transitions that are encountered around exceptional points has been shown to lead to many intriguing phenomena, such as loss-induced transparency4, unidirectional invisibility5, 6, band merging7, 8, topological chirality9, 10 and laser mode selectivity11, 12. Recently, it has been shown that the bifurcation properties of second-order non-Hermitian degeneracies can provide a means of enhancing the sensitivity (frequency shifts) of resonant optical structures to external perturbations13. Of particular interest is the use of even higher-order exceptional points (greater than second order), which in principle could further amplify the effect of perturbations, leading to even greater sensitivity. Although a growing number of theoretical studies have been devoted to such higher-order degeneracies14, 15, 16, their experimental demonstration in the optical domain has so far remained elusive. Here we report the observation of higher-order exceptional points in a coupled cavity arrangement—specifically, a ternary, parity–time-symmetric photonic laser molecule—with a carefully tailored gain–loss distribution. We

study the system in the spectral domain and find that the frequency response associated with this system follows a cube-root dependence on induced perturbations in the refractive index. Our work paves the way for utilizing non-Hermitian degeneracies in fields including photonics, optomechanics10, microwaves9 and atomic physics17, 18.



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