

A phonon laser operating at an exceptional point

July 20 2018, by Thamarasee Jeewandara



Schematic diagram of phonon lasing in a compound resonator system: two microtoroid resonators μ R1 (green) and μ R2 (blue), are coupled to each other by evanescent fields. The first resonator supports a high-Q optical mode a1, and a mechanical mode with resonance frequency Ω m. The second resonator μ R2, supports a low Q optical mode a2, and its damping rate is tuned by a chromium-coated silica nanotip approaching μ R2. Credit: *Nature Photonics*, nature.com/articles/s41566-018-0213-5

The basic quanta of light (photon) and sound (phonon) are bosonic particles that largely obey similar rules and are in general very good



analogs of one another. Physicists have explored this analogy in recent experimental investigations of a phonon laser to provide insights into a long-debated issue of how a laser—or more specifically, its line width—is affected when operated at an exceptional point (EP). Exceptional points are singularities in the energy functions of a physical system at which two light modes coalesce (combine into one mode) to produce unusual effects. Until recently, the concept mainly existed only in theory, but received renewed attention with <u>experimental</u> <u>demonstrations in optical systems</u> such as lasers and photonic structures. The experimental studies involved systems with <u>parity-time symmetry</u> for balanced gain and loss of material, to ensure robust light intensity, immune to backscatter. While closed and lossless physical systems are described by Hermitian operators in quantum physics, systems with open boundaries that exhibit exceptional points (EPs) are <u>non-Hermitian</u>.

Experimental studies of the EP mostly concern such parity-time symmetric systems that cleverly exploit the interplay between gain and loss to enable entirely new and unexpected features. In one such conceptual leap, unusual optical effects produced in these systems rendered the medium invisible in one direction, a step toward nextgeneration optical materials with unique properties not seen with natural materials. Such concepts have initiated intense research efforts to explore non-Hermitian systems both experimentally and theoretically.

Before the first laser was experimentally demonstrated, Schawlow and Townes calculated the fundamental quantum limit for its linewidth; EPs are historically associated with extreme broadening of the laser linewidth—beyond the fundamental Schawlow–Townes limit. Although theoretical models have provided a framework to calculate laser linewidth, they fail to resolve the problem directly at the EP. Experimentally, it is not straightforward to steer a laser directly to an EP, since photonic laser modes become unstable close to an EP, causing chaotic lasing that could be erroneously perceived as an extremely broad



laser line.

What really happens to the linewidth when a laser operates at an EP in practice has therefore remained unclear up until now. Understanding the mechanisms responsible for linewidth broadening will enable laser resources with new capabilities that we did not have access to before. Zhang *et al.*, provide an elegant new strategy to tackle this problem as published in *Nature Photonics*, by working with a phonon laser rather than its optical (photonic) counterpart, to observe its operation at an exceptional point.







Tuning a phonon laser to an exceptional point: the first column is a schematic of the distribution of the optical supermodes a± in the two resonators. The second column illustrates the frequency difference and linewidths of the two optical supermodes a±. The last column represents the linewidth of the phonon laser. The EP at which the two optical supermodes coalesce is at c, highlighted in red. The system transits from well separated and symmetrically distributed optical supermodes at a,b, to increasingly overlapping supermodes with complete overlap seen at c. Driven by the optical modes the phonon laser inherits the increased optical noise, reflected by a broadened mechanical linewidth (red box). The regime after the EP is seen at d, e, pushing the system away from the EP leading to linewidth narrowing of the phonon laser. Credit: *Nature Photonics*, nature.com/articles/s41566-018-0213-5

In the study, phonon lasers produce coherent sound oscillations (mechanical vibrations) induced by optical pumping, a concept previously developed by <u>Grudinin, Vahala and co-workers</u>, with characteristics typical for photon lasers. In the present experiment, the researchers used a similar optomechanical system with two coupled silica whispering-gallery-mode microresonators (green and blue). The compound phonon-laser system was steered toward or away from its EP to observe the behavior of phonon lasing near an EP.

To observe linewidth broadening, the physicists optically excited the mechanical mode of the experimental device with light from a tunable <u>laser</u> coupled to a single microresonator (green) by means of a tapered fiber. Then, to steer the system toward or away from its EP, they introduced additional loss to the second microresonator (blue) using a chromium-coated silica nanofibre tip.

The interplay between gain and loss was exploited in this way to tune a



phonon laser to an EP. Phonon lasing is interpreted as a three-wave parametric process in which two waves are optical and the third wave is acoustic or mechanical. Zhang et al. provided direct experimental evidence to show complete overlap of optical supermodes at EP, and that EP-enhanced optical noise can be transferred directly to mechanical noise, leading to the observed linewidth broadening in <u>phonon</u> lasers.

The practical benefits are easy to grasp: Sound waves propagate at a speed that is about five orders of magnitude less than the speed of light, and the wavelength of sound is thus correspondingly shorter than that of light of the same frequency. This feature can enable highly precise, nondestructive measurements and imaging, as well as achieve a high concentration of energy with focused sound waves. The present work opens new perspectives for the relationship between noise and non-Hermitian physics, with potential applications in related fields such as signal processing technologies. The system can be used as an on-chip phononic device analogous to fully integrated photonic devices for information processing. More interestingly, the studied platform can broaden insights in non-Hermitian physics by enabling the detection and control of EPs in two-level or multi-level systems.

More information: Jing Zhang et al. A phonon laser operating at an exceptional point, *Nature Photonics* (2018). <u>DOI:</u> <u>10.1038/s41566-018-0213-5</u>

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