OPTICS

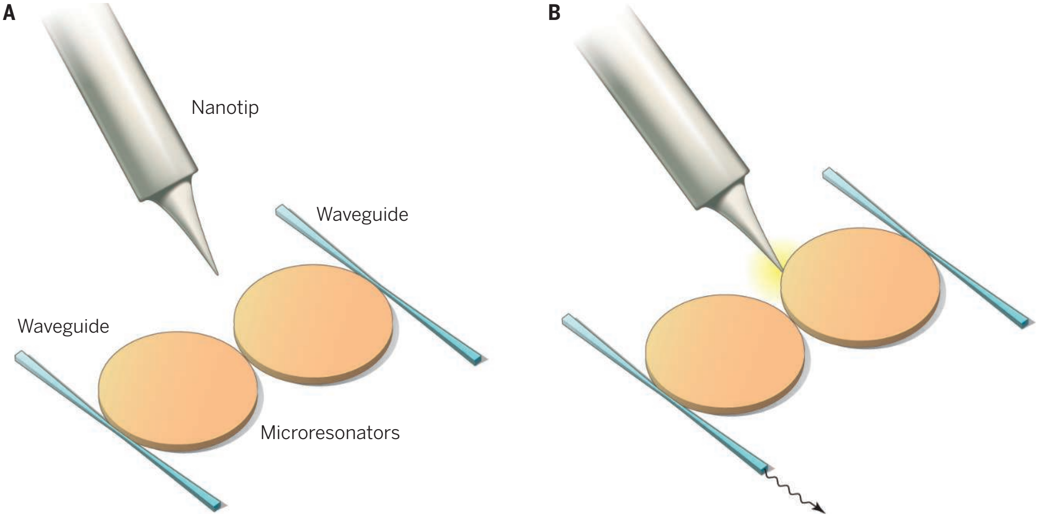
In optical pumping, less can be more

Creating loss in one optical resonator can initiate lasing in its coupled partner

By **Harald G. L. Schwefel**

Lasing is based on the process of optical gain. Once this gain provided through external pumping surpasses the loss in a resonator, lasing sets in and a coherent beam of laser light is emitted. Thus, loss is a natural adversary of lasing, at least in common lasers. A striking amendment to this rule is reported on page 328 of this issue by Peng *et al.* (*1*), who report an onset of lasing in a pair of coupled resonators when the total loss of the system is increased.

This special feature is possible because of the non-Hermitian nature of the system designed by Peng *et al.*, a property related to the Hamiltonian description that physicists use to calculate the time evolution of a system. When such a Hamiltonian is Hermitian, it means that the total energy is conserved, leading to real eigenvalues for the energy (as, for example, the energy of electrons in an atom). However, many realistic systems do not conserve energy. The corresponding gain and loss processes can be modeled through Hamiltonians that are non-Hermitian and which will generally have complex eigenvalues. A particular example is a laser, which features an amplifying medium (through optical gain) and radiates out a coherent laser beam (causing loss).



An odd laser at a loss. (**A**) Two coupled microresonators initially exhibit no lasing. (**B**) By increasing the loss in one microresonator through coupling to a nanotip (in silver), the other microresonator can suddenly start to lase (the light is coupled to the optical waveguides shown in blue). Peng *et al*. show how these effects are caused by the non-Hermitian nature of the system.

The physics that follows from such non-Hermitian properties shows several counterintuitive features, especially near so-called "exceptional points" (EPs) in parameter space, where two complex eigenvalues coalesce in both their real and imaginary parts. Recently, a specific subset of non-Hermitian systems with a so-called parity-time (PT) symmetry have surfaced for which the gain and the loss are carefully balanced so that the eigenvalues end up on the real axis (*2*). For such cases, surprising experimental results, such as loss-induced transparency (*3*), unidirectional invisibility (*4*), and optical isolation (*5*) have been demonstrated.

These PT-symmetric systems are, however, only a subset of the general class of non-Hermitian systems for which the eigenvalues reside in the complex plane. In particular, for systems operating near the lasing threshold, theoretical proposals indicate phenomena occurring near an EP, such as coherent perfect absorption of light (*6*) and the loss-induced onset of lasing (*7*) studied here. To venture experimentally through the vicinity of the EP, typically two independent parameters are necessary. Such parameters are accessible by coupling whispering gallery mode resonators, which efficiently trap light via total internal reflection at the rim of a convex shape made from a dielectric material (such as silica). When two spectrally identical optical resonators couple, they form a "photonic molecule," in that individual modes undergo a mode splitting similar to the transition for electronic levels when atoms form molecules (*8*, *9*). In the optical domain, individual tuning of the resonators is necessary to achieve degenerate modes and coupling between both resonators (*5*). The two independent parameters are the coupling strength, as determined by the distance between the two resonators, and the loss added by an absorptive nanotip probe in the vicinity of one of the resonator's evanescent field. Tuning of these two parameters allows the system to approach the EP.

Peng *et al.* used coupled whispering gallery mode resonators as a convenient platform to study several of the fascinating phenomena arising in the vicinity of an EP (*7*). When they brought two resonators near each other, the individual resonance modes split and supermodes formed with slightly detuned resonance frequencies (see the figure). When additional loss was induced by the optically absorbing nanotip, the resonance frequencies, given by the real part of the eigenvalues, lost their detuning when passing the EP. At this point, the imaginary parts of the eigenvalues, which describe the loss or gain of the mode, acquired a detuning at the EP that resulted in one of the two resonant modes experiencing less loss than the other. This imbalance is a direct consequence of the field distributions of the modes no longer being equally distributed between both resonators. Rather, with increasing nanotip loss, each mode is increasingly concentrated in one of the resonators alone.

To show the most striking effect resulting from this mode rearrangement at an EP, Peng *et al.* took advantage of silica microtoroids' ability to provide Raman gain when pumped by an appropriately offset pump laser (*10*). With this additional feature, the

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two coupled resonators were operated near the lasing regime. When adding loss by the nanotip, the detuning in the imaginary part of the eigenvalues reduced the loss of the mode in the resonator without the nanotip up to the point where the lasing threshold was reached, and the coupled system experienced a loss-induced onset of lasing.

The observation and control of an EP for a laser opens the way toward many further studies such as on self-pulsation effects in the temporal dynamics of the laser (*11*). A way to explore the fascinating topological aspects of EPs is to encircle them in the two-dimensional parameter space, parameterized by the nanotip-induced loss and the coupling strength. In passive resonators, a curious mode exchange and the accumulation of a geometric phase have been observed for this situation (*12*). How these phenomena translate to the lasing regime, where nonlinear mode interactions also play a role, is still an open question that may occupy both theorists and experimentalists in the years ahead.

> ***"The observation and control of an exceptional point for a laser opens the way toward many further studies..."***

Even beyond lasing, non-Hermitian systems can be found in many other contexts. In optical sensing, EPs can enhance single-particle detection (*13*), and in optomechanical systems, they can enable applications such as a phonon laser (*14*). Similar non-Hermitian concepts have even been applied to finance, where non-Hermitian Hamiltonians are used to describe stochastic financial instruments with striking effects that just wait to be explored. ■

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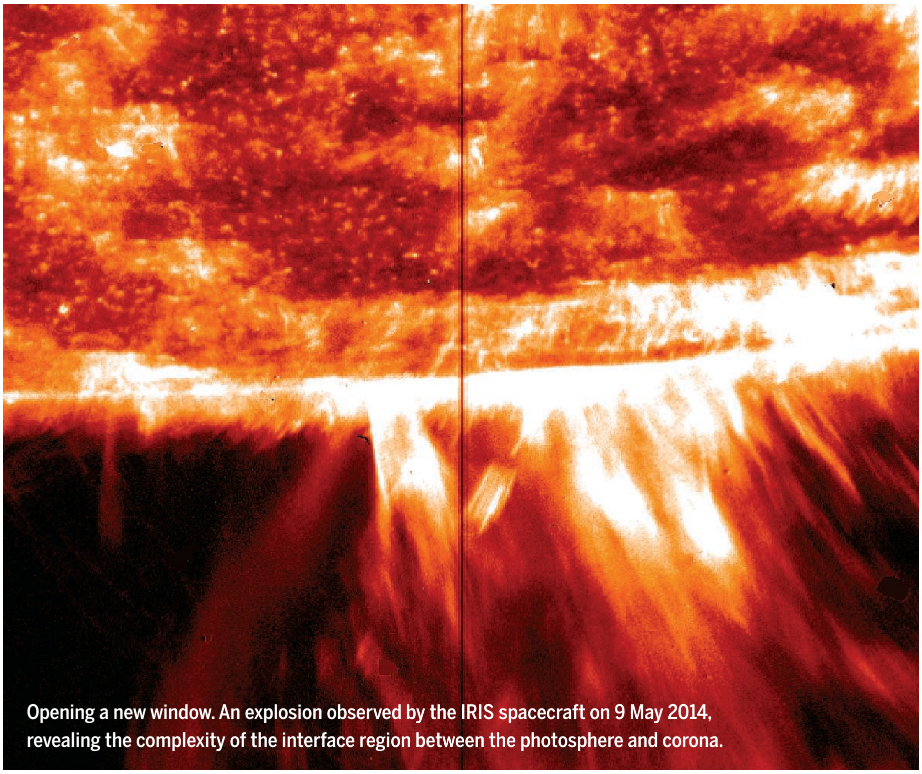

Opening a new window. An explosion observed by the IRIS spacecraft on 9 May 2014, revealing the complexity of the interface region between the photosphere and corona.

ASTRONOMY

Looking closer at the Sun

The space-based IRIS telescope provides a new window to view the solar atmosphere

By **Louise K. Harra**

The Sun's atmosphere is a dramatic and dynamically changing one. The physical domains encountered as the atmosphere is explored from the Sun's surface to the outer corona differ widely. The region where the differences are more notable is the interface region, where the plasma characteristics change from optically thick to optically thin and the regime goes from gas-dominated to magnetic-dominated. NASA's Interface Region Imaging Spectrograph (IRIS) (*1*–*5*) is now observing this elusive region. The first results from the mission are showing a world of twisted magnetic fields throughout the region, "bombs" exploding at regular intervals, evidence of particle acceleration causing heating in coronal loops, and small jets and loops appearing at cool temperatures. These results are providing important input into how the solar atmosphere is created and maintained and how the solar wind is formed.

The Sun is the largest object in the solar system, providing the heat and light that allows us to survive. It is a middle-aged star that produces energy through nuclear fusion of hydrogen to helium at its core. The enormous energies propagate through the interior of the Sun by radiation and convection. In the convection zone, the churning hot plasma creates magnetic fields. Our first view of the energy escaping the Sun is at the surface (the photosphere). Here, evidence of the convection that occurs in the interior is seen—the magnetic fields that appear help to form the heliosphere within which the planets are shrouded. The heliosphere drives the solar wind that flows past our planet, and is the source of large explosions that can affect our delicate Earth environment.

The magnetic fields are the source of the "coronal heating problem": As you move away from the Sun's surface (and farther from the heat source in the core), the tem-

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