MICROSENSORS

Exceptional points enhance wireless readout

In vivo sensors can be interrogated using a wireless system locked to an exceptional point, providing a sensitivity beyond the capabilities of standard wireless readout schemes.

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Wireless sensors are an important tool in healthcare. They can, for example, be used to monitor physiological parameters from within a person's body, helping manage chronic diseases including heart failure, brain injury and eye diseases. The development of battery-free (or passive) wireless implantable sensors, such as micromachined inductor–capacitor (LC) resonators (Fig. 1a), is an exciting trend in this technology because they allow stable and virtually maintenance-free operation.

The idea of a passive LC sensor was first proposed back in 1967, where it was used to measure pressure in the human eye in order to indicate the risk of glaucoma[1]. When the reader is placed near the sensor, the magnetic coupling between the reader and sensor inductors induces a change in the reader's radio-frequency spectral response, which can be used to analyse the state of the sensor. However, the practical use of implantable microsensors has been thwarted by limited improvements in the quality of the data and sensitivity they can offer, which are related to challenges associated with the need for devices with a small footprint. In particular, the magnetic coupling is generally too weak to cause a response that can be traced by an external wireless reader. In this issue of *Nature Electronics*, John S. Ho and colleagues[2] at the National University of Singapore now show that a wireless system locked to an exceptional point (EP) can enhance the sensitivity of wireless sensors in practical applications.

Exceptional points are non-Hermitian degeneracies where two or more eigenstates of a non-Hermitian Hamiltonian coalesce. Recently, exotic features of such branch-point singularities have been under intense investigation, especially in parity–time (PT)-symmetric optical setups[3–5]. In this context, photonics-based sensors that operate near EPs and provide enhanced sensitivity have been theoretically proposed[6] and later experimentally demonstrated[7,8]. In complementary efforts, PT symmetry was also implemented in electronic platforms[9], which has led to the development of EP-based wireless sensor systems with enhanced sensitivity[10,11]. These previous studies provided proof-of-concept demonstrations in well-controlled environments. In contrast, Ho and colleagues demonstrate an in vivo wireless sensor, which is based on a PT-symmetric reader circuit that is stably locked at an EP. The approach thus potentially provides a long-sought-after solution for bioimplants and wearable devices[2].

The researchers show, in particular, that their wireless sensor system can be used to interrogate a microsensor (with a diameter of 900 μm) that is implanted in a

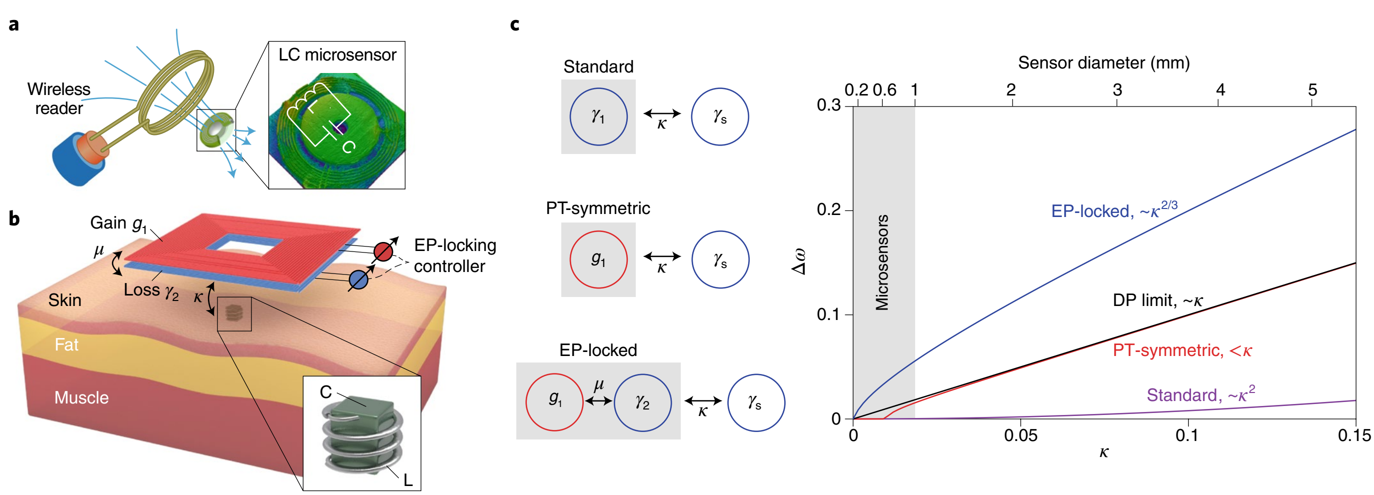

Fig. 1 | An EP-locked reader can wirelessly interrogate the state of a microsensor. a, Schematic of the battery-free and wireless LC microsensor system that exploits a coil reader to measure the biological information (for example, eye pressure) encoded in the radio-frequency spectral response. **b**, Illustration of the EP-locked reader developed by Ho and colleagues[2]. The reader is composed of the PT-symmetric electronic circuit with tightly coupled, balanced gain and loss. The motion of the LC microsensor affects the overall response of the reader circuit. **c**, Reader response is typically described by a transfer function that has zero(s) and pole(s), and the sensitivity is related to the dependency of the width of pole–zero split ($\Delta\omega$) on the strength of sensor-to-reader coupling (κ). A comparison of architectures (left) and sensitivities (right) of the standard reader, PT-symmetric reader and EP-locked reader is shown. Blue circles, resonators with different loss rates (γ), where subscript 's' stands for sensor; red circles, active resonators with gain (g). The EP-locked reader amplifies the response to microsensors, with $\Delta\omega \approx \kappa^{2/3}$. μ, internal coupling parameter; DP, diabolic point. Panels **b** and **c** are reproduced from ref. [2], Springer Nature Ltd.

rat. The motion of the rat's abdomen during respiration causes a dynamical variation in the inductive coupling between the reader and the sensor, and therefore the system can continuously track its breathing rate. The in vivo measurements show that the approach can offer a sensitivity that is 3.2-times beyond the limit encountered by standard wireless readout schemes. This is perhaps the first time that sensitivity is high enough for a sub-millimetre LC sensor to be wirelessly interrogated in a physiological environment.

The method of Ho and colleagues involves using a new type of reader that exhibits an EP by virtue of oscillatory circuits incorporating spatially separated, balanced gain and loss (Fig. 1b) — an arrangement that obeys PT symmetry[9]. The LC microsensor acts as an external perturbation onto the PT-symmetric reader circuit, with equal coupling rates to both the gain and loss resonators. The specially designed reader will amplify the spectral response under small perturbations of coupling rates, and thus enhance the reader's sensitivity for wirelessly interrogable passive microsensors.

In general, the response of the reader is characterized by a transfer function, defined as the amplitude ratio between the backward (output) and forward (input) signals assessed in the reader. Poles (ω_+) and zeros (ω_-) are the frequencies for which the value of denominator and numerator polynomials of the transfer function becomes zero, respectively. As the coupling strength between the reader and sensor inductors (κ) increases, the poles (eigenfrequencies) are forced apart from the zero (which is nearly stationary under specific conditions). The readout process for a wireless LC sensor can be understood by considering the width of split between pole and zero ($\Delta\omega = |\mathrm{Re}\{\omega_+ - \omega_-\}|$) as κ changes. A larger $\Delta\omega$ implies a greater modulation depth in the amplitude or phase spectrum, or a more conspicuous resonance-splitting phenomenon. In other words, the sensitivity of the reader is explicitly determined by the dependency of $\Delta\omega$ on κ. Interestingly, the eigenfrequency bifurcation in the EP-locked reader system results in a dependency of $\Delta\omega \approx \kappa^{2/3}$, well beyond the limit of the standard scheme (without incorporation of gain) that displays a square dependency on κ: that is, $\Delta\omega \approx \kappa^2$ (Fig. 1c). For an implanted microsensor, κ is usually quite small because of the implant depth and small dimensions of the sensor. Therefore, for a microsensor with $\kappa \ll 1$, this EP-locked technique may greatly enhance the sensitivity, owing to the $\kappa^{2/3}$ dependency. Moreover, the system exhibits a nontrivial EP-related degeneracy even when the reader and sensor are loosely coupled, for instance $\kappa \approx 0$. On the other hand, the exact PT-symmetric arrangement[11], comprised only of a reader equipped with gain and a passive microsensor, may be insensitive in the weak-coupling regime (Fig. 1c).

The wireless sensor system developed by Ho and colleagues is applicable in various health monitoring systems, as well as within clinical practice, which requires less-invasive and continuously functioning microsensors. The work also highlights the numerous opportunities that exist for further research on EPs and PT symmetry in electronic systems. For example, the fundamental limits of sensitivity enhancement at an EP remains an open question and higher-order EPs in optics have been shown to provide even greater sensitivity enhancement[7]. EPs also exist in systems of coupled resonators with unbalanced gain and loss factors[10], although the resolvability of the response could be different. Such unbalanced systems could be exploited to enhance the readout of high-loss sensors and to suppress electronic noises. Another important challenge is to engineer wideband and stabilized circuits capable of mitigating deterioration of the signal-to-noise ratio at an EP, as amplification of signals in active circuits is accompanied by increased noise. In this regard, multidisciplinary research, which combines applied physics, electronics and biomedical engineering, will be essential to maximize the potential of EP-associated bioelectronics and sensors. ❐

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