Ultra-sensitive PT-symmetric coupled cavities

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Abstract: We present a new class of ultra-sensitive PT-symmetric photonic molecules based on higher-order exceptional points. Methods to realize such sensitive structures are explored in InGaAsP arrangements by appropriately controlling the perturbations in the system.

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Optical microcavities are nowadays the subject of numerous studies, both in the scientific and technological domain. Their high quality factors can lead to strong light-matter interactions- a highly desirable attribute in many applications, especially those pertaining to sensing. Optical sensors can transduce small physical or chemical changes in the cavity's environment into a shift of the resonant frequency, which can be then detected [1]. However, improving the detection limit of these devices is often hindered by the resonator's Q-factor and the available spectroscopic resolution. Clearly of importance will be to devise new methodologies capable of improving the sensitivity of such devices. In this study, we propose a novel class of ultra-sensitive photonic molecules based on the physics of higher-order exceptional points in PT-symmetric arrangements.

Recently, the concept of parity-time symmetry has received considerable attention in the field of optics and photonics [2]. Along these lines, coupled micro-resonators provide an attractive platform to investigate some of the ramifications of PT-symmetry and the associated exceptional points [3,4]. For instance, second order exceptional points (EP-2) have been demonstrated in PT-symmetric active photonic dimers (Fig.1(a)) [3-5]. Interestingly, higher-order exceptional points (EP-N) are also possible in N-resonator systems designed by following a recursive bosonic quantization technique [6]. Examples of such PT-symmetric arrangements possessing an EP-3 and EP-4 are shown in Fig.1 (b) and (c), respectively. For such systems, at a critical value of the gain/loss contrast with respect to the coupling strength (κ), an EP-N point can emerge, where all the eigenfrequencies and their corresponding eigenmodes become identical.

To understand the principle behind the proposed method, let us consider a photonic molecule comprised of N cavities. The modal fields of such a structure obey the evolution equation $id\vec{V}/dt = M_0\vec{V}$, where $\vec{V}$ is the modal column vector of dimensionality N and M_0 is an $N \times N$ non-Hermitian matrix that plays the role of an optical Hamiltonian. Around standard degeneracies, if the Hamiltonian is perturbed to order ε (i.e. $M = M_0 + \varepsilon M_1$, where M_1 is in general non-Hermitian), then as is well-known, the system's eigenvalues will also be perturbed at most to order ε - $\Delta\lambda \sim \varepsilon$. This splitting of eigenvalues or eigenfrequencies has been so far utilized in a number of sensing schemes [1]. On the other hand, around an exceptional point, the response of a system to small variations is expected to be even more drastic [7]. For example, in a 2-level PT-symmetric arrangement (Fig.1(a)), supporting an EP-2, the eigenvalues

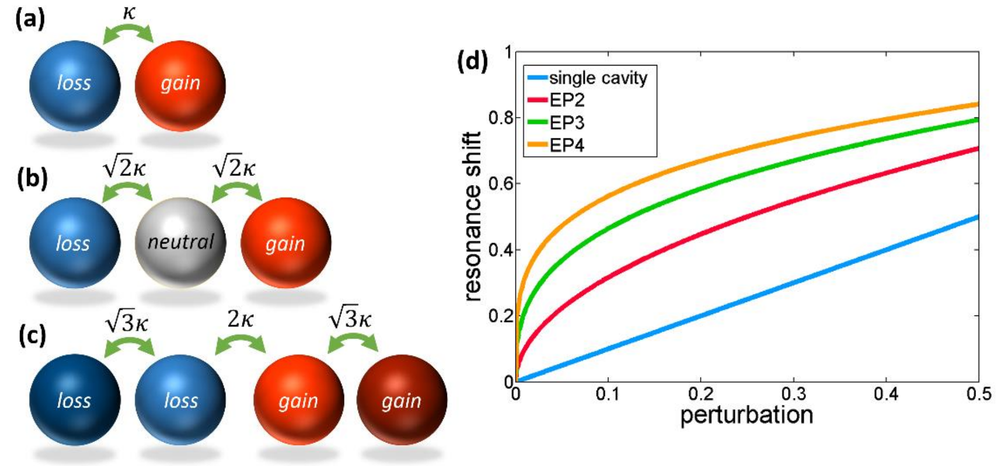

Fig 1. PT-symmetric coupled cavity configurations supporting a **(a)** second order, **(b)** third order, and **(c)** fourth order exceptional point. **(d)** The shift in the cavity's resonant frequency as a function of perturbation strength.

are now perturbed according to $\Delta\lambda \sim \varepsilon^{1/2}$. This suggests that the system's response (eigenfrequencies and their associated growth or decay rates) is in this case considerably more sensitive to external disturbances since the function $\sqrt{\varepsilon}$ magnifies perturbations when compared to a linear ε dependence. Accordingly, in more complex systems supporting EP-Ns ($N > 2$), the presence of a higher-order exceptional point leads to highly pronounced changes in the spectrum due to perturbations, given that the splitting of eigenfrequencies follows a $\Delta\lambda \sim \varepsilon^{1/N}$ behavior. In other words, around an EP-**N** point the system becomes ultrasensitive to external disturbances. To illustrate this enhancement in sensitivity around an EP-2, EP-3, and EP-4, the function $\varepsilon^{1/N}$ ($N = 2{:}\,4$) is plotted with respect to ε in Fig. 1(d).

In order to experimentally assess the efficacy of this method, the proposed systems can be realized using coupled ring resonators comprised of InGaAsP quantum wells. Such resonators typically have a $Q \sim 120{,}000$ and when pumped exhibit a modal gain exceeding $100\ cm^{-1}$. On the other hand, the un-pumped cavities experience losses on the order of $50\ cm^{-1}$. In such arrangements, given that the coupling strengths are fixed by the separation between neighboring rings, the system can be brought to a higher-order exceptional point by adjusting the gain/loss contrast through the spatial distribution of the pump. Perturbations can be introduced via thermo-optic detuning of the micro-cavities using electrical heating elements. Figure 2(a) depicts a schematic of this design for a double PT-symmetric microring system, where a heater is placed on one of the rings for local temperature control. The inset shows a microscope image of such a structure. The large intrinsic thermo-optic coefficient of the semiconductor gain material translates to a resonant wavelength shift of 0.1 nm/K- in good agreement with measured dn/dT values reported in the literature. Finally, the wavelength shift in a PT-symmetric arrangement can be measured and compared to that of a single ring. The expected response of this configuration is depicted in Figs. 2 (b) and (c) where the spectra associated with an unperturbed and perturbed PT-symmetric photonic dimer when operating at the exceptional point are shown. In this case, the resonant frequencies will split following a $\varepsilon^{1/2}$ behavior. Our design provides an important step towards utilizing higher order exceptional points associated with PT-symmetric configurations to enhance the detection characteristics of micro-cavity systems.

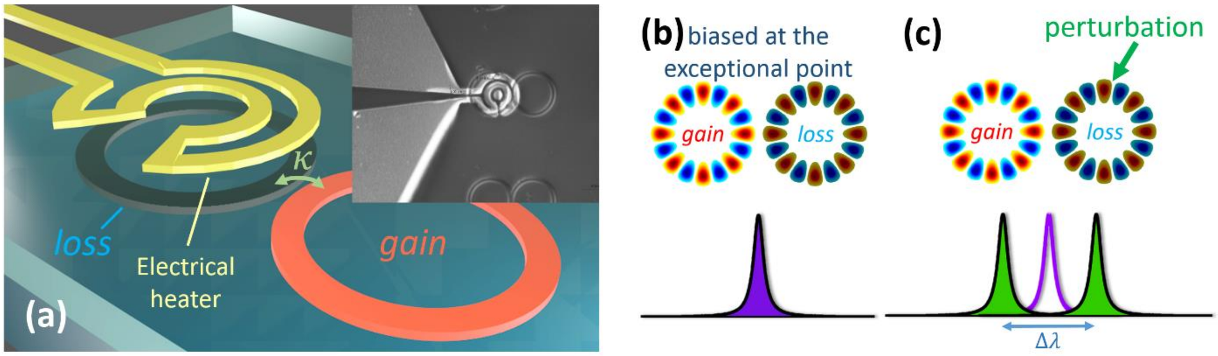

Fig. 2. Proposed scheme to demonstrate enhanced sensitivity in a PT-symmetric coupled cavity arrangement. The inset shows a microscope image of a fabricated structure. An electrical heater (yellow) is positioned on top of one of the rings to introduce thermal perturbations. (b) A PT dimer biased to operate at the exceptional point displays only one resonance (c) The resonant frequencies split significantly as a result of a perturbation.

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