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Exceptional points with waveguide-coupled nanolasers

Guilhem Madiot[1,*], *Patricia* Loren[1], *Alexandre* Bazin[2], *Quentin* Chateiller[2], *Isabelle* Sagnes[2], *Grégoire* Beaudoin[2], *Konstantin* Pantzas[2], and *Fabrice* Raineri[1]

[1] Université Côte d'Azur, CNRS, Institut de Physique de Nice, 06200, Nice, France
[2] Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Saclay, 10 Bd Thomas Gobert, 91120 Palaiseau, France

Abstract. Exceptional points (EPs) attract lots of attention due to the richness of the phenomenology associated to their presence in the complex eigenspectrum of coupled non-Hermitian systems. Here we provide both a coupled mode theory analysis and an experimental investigation of two nanolasers interacting through a channel-mediated coupling. We demonstrate the transition from Parity-Time (PT) symmetric to PT-broken regime using a thermo-optic control over the laser frequency detuning

1 Introduction

Within the scope of non-Hermitian photonics, numerous recent works have proven that the exploitation of losses in optical systems might be particularly meaningful to achieve novel functionalities for future photonic circuits [1]. Exceptional points (EPs), emblematic concepts of this domain, are singularities in the parameter space of coupled dissipative oscillators [2-3]. They are defined by the coalescence of at least two eigenvalues and of their associated eigenvectors. EPs are markers of Parity-Time symmetry breaking and their presence coincides with several important functionalities such as spectral or spatial non-reciprocity, loss-induced transparency, or enhanced sensing. Most experimental implementations allow to reach EPs making use of purely dispersive coupling. This is generally obtained via a nearest-neighbour evanescent coupling between two resonators with identical natural frequencies but opposite dissipation rate; i.e. in a gain-loss configuration. The basic theoretical analysis of such system shows that the EPs in this case are revealed by scanning the gain (or loss) coefficient. In this work, we use a waveguide-mediated complex coupling between two distant laser nanocavities, such that Eps can be reached using either or both spectral detuning of gain-loss parameters. Adopting optical pumping to control the gain in each cavity associated with thermo-optic spectral shifting methods, we demonstrate a full control over the intrinsic properties of both nanocavities; enabling us to envision precise exploration of their complex eigenspectrum. The experiment is realized while both nanolasers are pumped below their respective threshold, which enables to perfectly identify a loss-splitting between the eigenmodes.

2 Coupled mode theory description

First, let us consider two cavities with respective natural angular frequencies ω_1 and ω_2, total amplitude decay rates Γ_1 and Γ_2 and both coupled to the same waveguide with an identical external coupling rate Γ_c. The optical wave travelling into the waveguide accumulates a phase shift $\phi = \frac{2\pi n_{eff} d}{\lambda}$ between the resonators, where d is the distance that separates them, n_{eff} the effective refractive index of the optical waveguide, and λ the wavelength. Coupled Mode Theory principles applied to this configuration provide the effective coupling between the cavities, $K = j\Gamma_c e^{j\phi}$ and the two complex eigenvalues:

$$\Lambda_{\pm} = \overline{\omega} - j\overline{\Gamma} \pm \sqrt{(\delta\omega - j\delta\Gamma)^2 - K^2}$$

Where we introduce $\overline{\omega} = (\omega_1 - \omega_2)/2$, $\overline{\Gamma} = (\Gamma_1 + \Gamma_2)/2$, $\delta\omega = (\omega_1 - \omega_2)/2$ and $\delta\Gamma = (\Gamma_1 - \Gamma_2)/2$. Note that, in this formalism, the eigenmodes frequencies and decay rates write $\omega_{\pm} = \mathrm{Re}(\Lambda_{\pm})$ and $\Gamma_{\pm} = -\mathrm{Im}(\Lambda_{\pm})$. Thus, this approach confers a complex coupling which can go from purely dispersive – as expected with a nearest-neighbor evanescent coupling ($\phi = \pi/2$ [π]) – to purely dissipative coupling ($\phi = 0$ [π]). Additionally, it can be shown that for a given phase ϕ, two exceptional points can be reached when

$$\delta\omega_{EP} = \pm\Gamma_c \cos\phi$$

$$\delta\Gamma_{EP} = \mp\Gamma_c \sin\phi$$

Hence it is necessary to exert independent control over the cavity detuning $\delta\omega$ and the decay rate difference $\delta\Gamma$ in order to reach these positions in the parameter space.

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[*] Corresponding author: gmadiot@unice.fr

3 Experimental results

We implement this configuration by using two photonic crystal InP-based nanolasers integrated on top of a SOI photonic waveguide. A scanning electron micrograph of the nanolaser is depicted in Fig. 1.a. A 1064 nm diode laser is focused on each nanolaser to pump its active medium. The nanolaser emission is collected at the waveguide outputs using two optical fibers, and sent into a near-infrared spectrometer. Although the two nanolasers have identical nominal geometries, residual fabrication imperfections lead to a natural detuning of the order of 1 nm in their natural resonance wavelength (in absence of optical pumping). To counterbalance this asymmetry, a thermo-resistive gold nanowire is enclosed to each cavity enabling thermo-optic control over its refractive index. By measuring a nanolaser emission spectrum as a function of the current applied to the associated thermo-heater, we plot the nanolaser emission wavelength as a function of the current in Fig. 1.b and fit the data (black circles) with a quadratic function, $\lambda(I_{th}) = \lambda(0) + \alpha_{th} \times P_{th}$ with $P_{th} \approx RI_{th}^2$ the heating power and $R \approx 55\ \Omega$ the thermo-heater measured resistance. The fit returns a heating efficiency $\alpha_{th} \approx 1.42$ nm/mW.

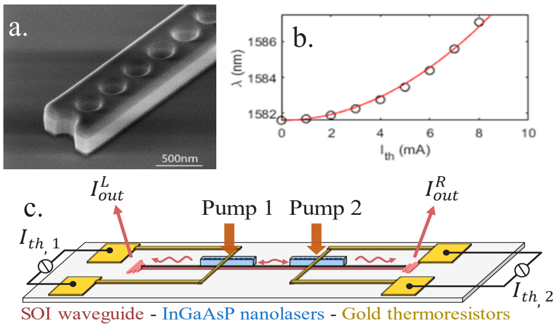

Fig. 1. a. SEM micrograph of one InP photonic crystal nanolaser [4]. b. Measured emission wavelength as a function of the applied thermo-resistance current. c. Schematic of the 2-nanolasers sample including optical pumps, thermo-heaters and collection at the waveguide output.

Setting the two nanolasers below their respective laser thresholds (weak pump powers $P_1 \approx P_2 < 1$ mW), we measure the output spectrum while increasing the detuning shown here in terms of a cavity resonance wavelengths difference $\delta\lambda \equiv \lambda_2 - \lambda_1 \propto \delta\omega$. Far-detuned nanolasers lead to uncoupled eigenmodes settling loss regimes as can be seen in Fig. 2.a for δλ>3 nm. However, when coupling occurs, the eigenmodes show large splitting dominated by a dissipative component such that one eigenmode is broad and hidden below the other one, much narrower. Both modes have almost aligned resonant frequencies. Both regimes are illustrated with representative spectra in Fig. 2.b. Importantly, the eigenmode with lower dissipation rate approaches its lasing threshold which implies a strong enhancement of the emission.

4 Conclusion

In this work, we have proposed a scheme to introduce complex coupling between two photonic resonators. The

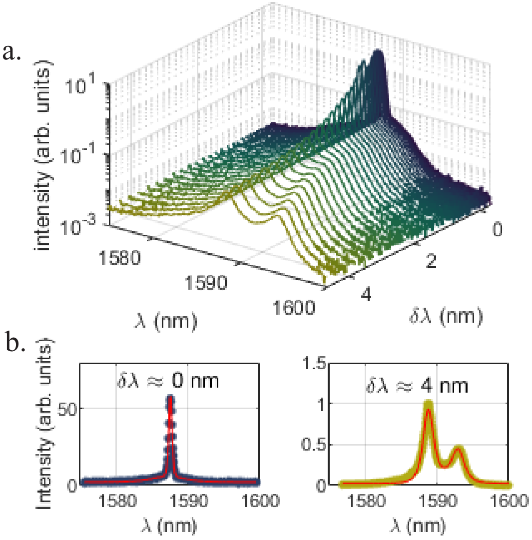

Fig. 2. a. Measured output spectrum as a function of cavity detuning $\delta\lambda=\lambda_2-\lambda_1$. b. The splitting is dominated by a dissipative component (left spectrum); or by a dispersive component (right spectrum);. Data (dots) are fitted with a double-voigt peak function (red lines).

coupled mode theory analysis of the system has been applied and the presence of exceptional points in the eigenspectrum has been described as a function of cavity dissimilarities. In addition, we have provided an experimental demonstration of PT-symmetry broken laser emission employing a thermo-optic control over the cavity natural resonance wavelength. This work constitutes a first step in the realization of finely controlled exploration of non-Hermitian photonics with strongly nonlinear systems. The same experiment in the laser regime would pro-vide interesting insights on the way EPs can be described in the presence of optical nonlinearities [5,6].

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