Chiral Perfect Absorption on Exceptional Surfaces

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Abstract: We demonstrate an exceptional surface in a waveguide-coupled resonator by establishing unidirectional coupling between its frequency-degenerate counterpropagating modes. When operated on the ES, the system exhibits chiral perfect absorption with quartic lineshape.

Exceptional points (EPs) are generic degeneracies observed in non-Hermitian systems, where two or more eigenvalues and their corresponding eigenvectors coalesce [1-2]. Chiral behavior [3], enhanced sensitivity to perturbations [4], and enhanced transmission and lasing with increasing loss [5] are among many interesting features observed when a system is operated in the vicinity of an EP. Since EPs are discrete points in the parameter space of the system, tuning the system to operate at an EP and stabilizing it against fabrication errors and fluctuations in the experimental setup is a challenge. Exceptional surfaces (ES), which are hypersurfaces formed by a continuous collection of EPs in the parameter space of a system, are proposed to overcome this challenge [6]. Here, we demonstrate an exceptional surface in an on-chip waveguide-coupled whispering-gallery-mode (WGM) microsphere resonator by establishing unidirectional coupling between its frequency-degenerate clockwise (CW) and counterclockwise (CCW) modes. This is achieved by terminating only one end of the waveguide, which is used to couple light into and out of the resonance mode, by a tunable symmetric mirror. This configuration ensures that the light input in one direction, say CW, is transmitted to the end-mirror and is back-reflected to couple into the CCW mode whereas the light input in the opposite direction, say CCW, is transmitted without coupling to CW mode. The tunable end-mirror allows us to control the strength of the unidirectional coupling [7].

Figure 1 presents the concept of the realizing an ES surface in a waveguide coupled resonator and an illustration of our experimental setup together with an optical microscope image of the on-chip WGM silica microsphere used in the experiments. Light is coupled in and out of the resonance mode using a tapered fiber. The fiber loop with polarization controller is used as a tunable end-mirror to control directional coupling from CW to CCW mode. Phase shifter (PS) is used to change the phase of the reflected light from the fiber- loop mirror. In the absence of the end-mirror, the reflection and transmission spectra for inputs in the CW and CCW directions are the same, that is the system is symmetric. We confirmed that there is no initial intermodal coupling (i.e., no mode splitting). Within the context of coupled-mode theory, this system is described by $\partial_t A = -iH_{ES}A$ where $A = (a_{cw}, a_{ccw})^T$, a_{cw} and a_{ccw} are the field amplitudes of the CW and CCW modes respectively, and H_{ES} is the effective Hamiltonian given as

$$H_{ES} = \begin{pmatrix} \omega_0 - i\Gamma & 0 \\ \kappa & \omega_0 - i\Gamma \end{pmatrix} \quad (1)$$

In Eq. (1), $\omega_0 - i\Gamma$ are the complex frequencies of the degenerate CW and CCW modes, with $\Gamma = (\gamma_0 + \gamma_1)/2$ corresponding to the cavity loss rate which consists of the waveguide coupling loss γ_1 and all other resonator related losses (i.e., radiation, scattering and material absorption losses) γ_0, and κ denotes the CW-to-CCW coupling strength.

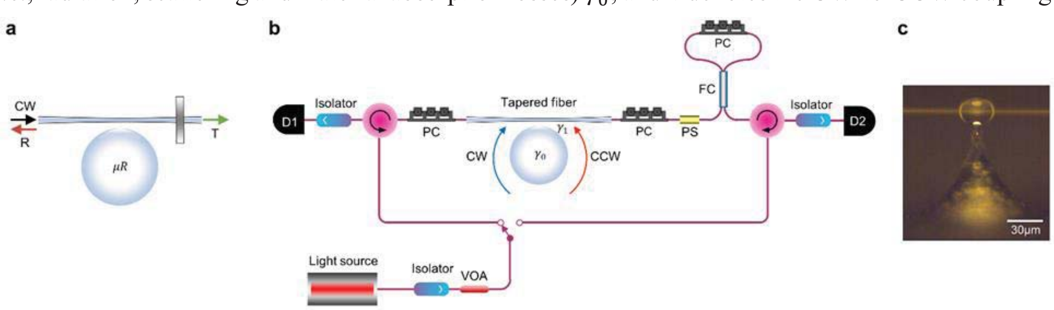

Fig. 1. (a) The concept of establishing unidirectional coupling in a microresonator (μR) with an end mirror. (b) Experimental setup. (c) An optical image of the tapered-fiber coupled on-chip microsphere resonator. $\boldsymbol{\gamma_1}$: coupling loss; $\boldsymbol{\gamma_0}$: resonator related losses; PC: polarization controller, FC: 2-by-2 fiber coupler; PC: polarization controller, VOA: variable optical attenuator, D1 & D2 are photodetectors.

The eigenvalues and the corresponding eigenvectors of this system are degenerate and given as $\omega_{1,2} = \omega_0 - i\Gamma$ and $a_{1,2} = (0,1)^T$, forming an EP with CW chirality at the complex frequency $\omega_0 - i\Gamma$. Clearly, the system is at an EP for any non-zero κ and for all values of ω_0 and Γ. In our system, $\kappa = r\gamma_1$ with $r = |r|\exp(i\phi)$ and $|r|$ and ϕ corresponding to the magnitude and phase of back-reflection from the end-mirror (i.e., fiber-loop mirror). Indeed, if $|\alpha|$ and ϕ are steered the system traces a surface formed by EPs, and hence an ES at the complex ES frequency $\omega_0 - i\Gamma$. The transmission and reflection spectra of this system for inputs in the CW and CCW directions when the waveguide-resonator system is operated at the critical coupling are given by $T_{cw(ccw)} \propto 1/(1+{\gamma_0}^2/\Delta^2)$, $R_{cw} \equiv |r_{cw}|^2 \propto 1/(1+{\gamma_0}^2/\Delta^2)^2$ and $R_{ccw} = 0$. With the reflection and transmission spectra known, we can then find the absorption spectra using $A_{cw(ccw)} = 1 - T_{cw(ccw)} - R_{cw(ccw)}$. It is clear that [7]: i) transmission for CW and CCW inputs is symmetric and has Lorentzian lineshape (i.e., quadratic lineshape); ii) the system has asymmetric reflection, that is reflection for the CW input have squared Lorentzian lineshape (i.e., quartic lineshape) while the reflection for the CCW direction is a constant value; and iii) system has asymmetric absorption, where the absorption lineshape for CCW input is Lorentzian and that for CW input is a superposition of Lorentzian and squared-Lorentzian lineshapes. Figure 2a and 2b shows the ES reconstructed from the experimentally obtained reflection spectra for an input in the CW direction at the critical coupling. A typical experimentally obtained reflection spectrum R_{cw} and calculated absorption spectrum A_{cw} at the critical coupling when mirror reflectivity was set to $|r| = 1$ are given in Fig. 2c. Squared-Lorentzian lineshapes with flattened resonance dip and peak around the ES frequency are clearly seen for R_{cw} and A_{cw}, respectively. Moreover, we have $A_{cw} = 1$ implying perfect absorption (i.e., in this configuration because the end-mirror is fully reflective, we have $T_{cw} = 0$). Figure 3a, b depicts the absorption obtained at the ES frequency at various values of the end-mirror reflectivity $|r|$ and the resonator-waveguide gap which determines γ_1 for inputs in the CW and CCW directions. Figure 3c clearly show that the absorption is chiral, that is $A_{cw} > A_{ccw}$, with higher chirality at higher $|r|$ and at taper-resonator gaps closer to the critical coupling condition.

In conclusion, we have demonstrated a non-Hermitian optical device which exhibits ES and chiral perfect absorption with quartic lineshape in reflection and absorption spectra. Since the device operates on an ES, it is always at an EP, providing a stable and tunable platform to study EP-related phenomena and processes.

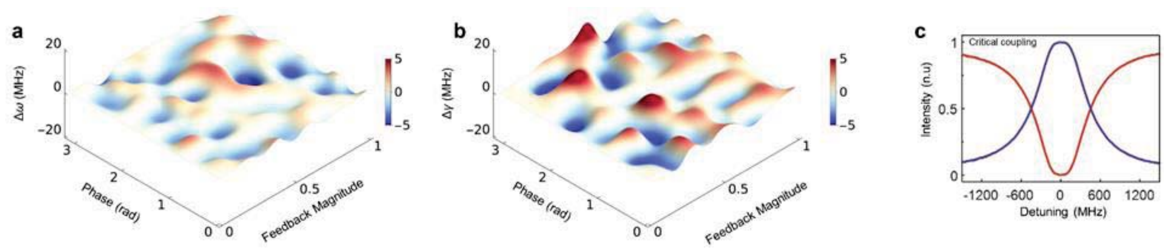

Fig. 2. (a), (b) Exceptional surface reconstructed from experimentally obtained reflection spectra for an input in the CW direction when the system was at critical coupling. Δω and Δγ corresponds, respectively, to the difference between the real and imaginary parts of the complex eigenfrequencies obtained from curve fitting to experimental data. (c) Absorption (blue) and reflection (red) spectra obtained at critical coupling when $|r| = 1$.

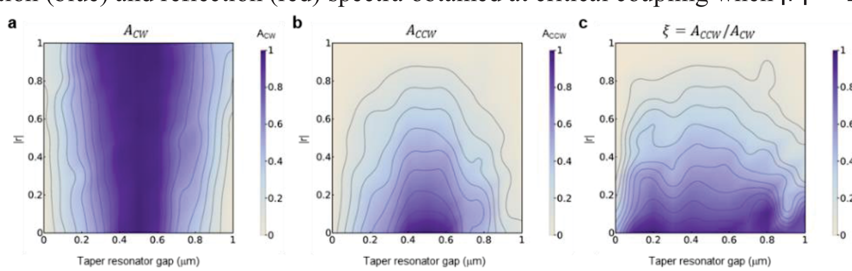

Fig. 3. Tunable chiral absorption on an ES. $\xi = 1$ corresponds to symmetric absorption.

References

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