Active tuning of silicon photonic microring resonator towards a chiral exceptional point

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Abstract: We demonstrate a silicon photonic passive PT-symmetric structure operating at an exceptional point, with dynamic mode-splitting tunability enabled by a local heater.

1. Introduction

Exceptional points (EPs) are non-Hermitian spectral degeneracies where both the eigenvalues and the corresponding eigenstates of a system coalesce. Optics has been a fertile field to study the EP physics and the effects of EPs on wave transport and control [1-3]. Among many interesting features revealed at an EP are loss-induced lasing, unidirectional reflectionless light transport and enhanced response to external perturbations [4-5]. A majority of these studies has been carried out using microring resonators that are either designed to operate at an EP with no tunability after fabrication or steered to an EP after the fabrication process by tuning the loss or scattering profiles via nanotips and scatterers introduced into the resonator's mode volume. Although the latter provides a tunability to study periodic chiral EPs in ring resonators, it is difficult to work with due to instabilities and vibrations, and hence not it is not practical. Therefore, easy to implement tuning methods are needed for practical use of chiral EPs. In this work, we propose and demonstrate a novel technique to controllably tune a silicon microring resonator to and away from chiral EPs. We achieve this by thermally tuning the optical path lengths between two spatially separated scattering centers of different shapes and sizes introduced into the mode volume of a silicon microring resonator during its fabrication. While a rectangular scatterer symmetrically couples the clockwise CW and counterclockwise CCW modes of the resonator, a triangular scatterer introduces and controls asymmetric coupling between CW and CCW modes (Fig. 1). Tuning their optical path difference by a local heater fabricated with the microring then helps steer the system to and away from EPs. We think the proposed method will open a new direction for the use of passive silicon photonics platforms to study EPs and EP-related concepts towards practical applications.

2. Design principle

To introduce exceptional points in a resonator, it is essential either by deforming its shape or introducing defects structure providing asymmetric scattering between CW and CCW modes. At this chiral EPs, the ring resonator predominantly supports either CW or CCW component. We design a symmetric rectangular defect

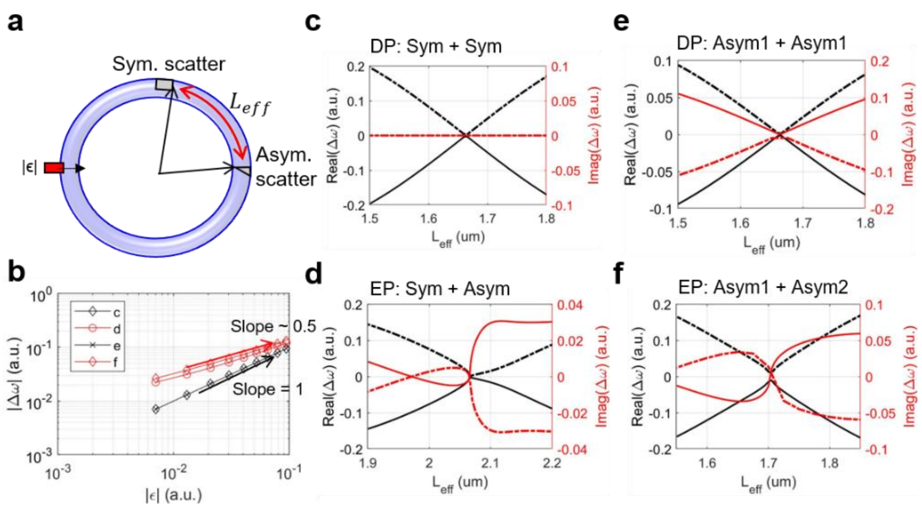

Figure 1 | Asymmetric coupling induced EP in a microring resonator. (a) Schematic diagram of a microring resonator with scatterers in which chiral EPs emerge due to asymmetric coupling between CW and CCW modes. A rectangular symmetric (Sym.) and a triangular asymmetric (Asym.) scatterer with specific dimensions and spacings are defined on the perimeter of the microring resonator. (b) Amount of mode splitting versus perturbation strength in the systems with DP ((c) and (e)) or EP degeneracies ((d) and (f)). Splitting in the real and imaginary parts of the eigenfrequency as a function of the distance L_{eff} between (c) two symmetric scatterers, (d) one symmetric and one asymmetric scatterer, (e) identical asymmetric scatterers, and (f) different asymmetric scatterers.

("Sym") and an asymmetric triangular defect ("Asym") to introduce symmetric or asymmetric backscattering in our system. A non-Hermitian system formed by combinations of two different scatters ("Sym" or "Aysm") can be described by a 2 × 2 matrix, where the off-diagonal elements represent the coupling strength (complex numbers) between CW and CCW modes. We calculated these complex coupling strengths through numerical simulations. Without considering fabrication tolerance at this moment, we found that EP emerges in two cases (Fig 1(d) and Fig 1(f)), where the relative distance between a symmetric and asymmetric scatter is finely adjusted. In the cases when two symmetric scatterers or two identical asymmetric scatterers are considered, only DP degeneracies emerge (Fig 1(c) and Fig 1(e)). We compared these cases by introducing a third scatterer, simulating a perturbation of strength $|\epsilon|$, and calculating the amount of mode splitting (Fig 1(b)). We found that while the response of the systems operating at a DP scales linearly with ϵ, the response of the systems operating at an EP scales with $\sqrt{\epsilon}$ as expected.

3. Experiment

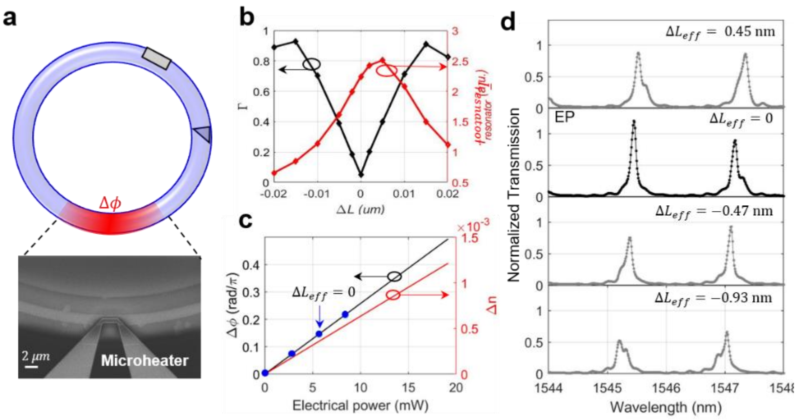

Figure 2 | Tunable EP system. (a) Schematic diagram of a microring resonator with a symmetric and an asymmetric scatterer whose relative distance is thermally tuned to bring the system to an EP. (Inset) SEM image of ring resonator and integrated microheater which helps tune the system by local heating (Inset) SEM image of integrated local heater. The microheater is deposited on top of 1µm oxide cladding (5 µm length, 920 nm width). (b) Numerically simulated electric field amplitude ratio of CCW and CW modes in the microring versus effective length difference between the scatterers. $\Gamma = (\sqrt{I_{max}} - \sqrt{I_{min}})/(\sqrt{I_{max}} + \sqrt{I_{min}})$ is the reflection coefficient. (c) Measured phase shift $\Delta\phi$ (left axis) and change of refractive index (right axis) versus heating power. (d) Measured transmission spectra on drop port at increasing heating power, where ΔL_{eff} is converted by: (exp(-j $\Delta\phi$) = exp(-j$\beta_o \Delta L_{eff}$)).

As the mode-splitting is highly sensitive to ΔL_{eff}, fine tuning of the parameter is critical to get EP and DP. To achieve EP in the designed topology ("Sym"+"Asym"), we fabricated a microheater on the perimeter of the ring (Fig. 2a). The metal layer is defined by E-beam lithography on the double resist and deposited by dual electro-beam evaporator (Pt: 100 nm, Ti: 5nm). The microheater (5 µm by 920 nm) provides localized phase shift to compensate fabrication variations (Fig 2(a) inset). FDTD simulation (Fig. 2b) shows that the ratio of the CW and CCW components is highly sensitive to fabrication variations. The ratio of the CW and CCW modes and the average light intensity in the microring changes dramatically with ΔL_{eff}. In the experiments, we measured the effective phase shift in the ring versus the heating power applied to the local heater (Fig. 2(c)). The transmission spectra on the drop port are recorded in the highlighted power level (Fig. 2d). By finely adjusting the phase difference, we effectively tuned mode splitting to be zero where the extinction ratio (the ratio of CW and CCW modes) became maximal, indicating the emergence of an EP. To compare the experiment and theory, we converted the total phase shift induced by the local heater to the change of effective length (ΔL_{eff}).

4. Conclusion

We introduced a novel design principle and fabricated an electro-optically tunable microring resonator operating close to an EP. The demonstration of a tunable device which can be steered to and away from a chiral EP on a silicon photonic platform will pave the way to a number of novel silicon photonic components utilizing EP concepts.

5. References

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