Accessing the exceptional points of parity-time symmetric acoustics

Chengzhi Shi et al.

Outline

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Group introduction

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- UC Berkeley
- Field: Metamaterials, Nanophotonics, 2D Materials, Energy
- Postdoctoral researchers: 14
- Graduate students: 16

- They say: We are a highly interdisciplinary research group in nanoscience and engineering, with expertise in optical and electrical measurements, material synthesis, and theoretical modeling. Our research has primarily focused on the interaction of light with nanostructures, leading to exotic electromagnetic properties not found naturally.

Recent papers

298	Z. Chen, X. Wang, Y. Qi, S. Yang, J. A. N. T. Soares, B. A. Apgar, R. Gao, R. Xu, Y. Lee, X. Zhang, J. Yao & L. W. Martin, "Self-Assembled, Nanostructured, Tunable Metamaterials via Spinodal Decomposition." ***ACS Nano***, 10, 2016.	2016
297	J.-W. Dong, X.-D. Chen, H. Zhu, Y. Wang & X. Zhang, "Valley photonic crystals for control of spin and topology." ***Nature Materials***, AOP, 2016.	2016
296	Z. J. Wong, Y.-L. Xu, J. Kim, K. O'Brien, Y. Wang, L. Feng & X. Zhang, "Lasing and anti-lasing in a single cavity." ***Nature Photonics***, AOP, 2016.	2016
295	H. Dalir, Y. Xia, Y. Wang & X. Zhang, "Athermal Broadband Graphene Optical Modulator with 35 GHz Speed." ***ACS Photonics***, 3, 2016.	2016
294	H. Ramezani, M. Dubois, Y. Wang, Y. R. Shen & X. Zhang, "Directional excitation without breaking reciprocity." ***New Journal of Physics***, 18, 2016.	2016
293	M. Zhao, Z. Ye, R. Suzuki, Y. Ye, H. Zhu, J. Xiao, Y. Wang, Y. Iwasa & X. Zhang, "Atomically phase-matched second-harmonic generation in a 2D crystal." ***Light: Science & Applications***, 5, 2016.	2016
292	M. Zhao, Y. Ye, Y. Han, Y. Xia, H. Zhu, S. Wang, Y. Wang, D. A. Muller & X. Zhang, "Large-scale chemical assembly of atomically thin transistors and circuits." ***Nature Nanotechnology***, 11, 2016.	2016
291	K. L. Tsakmakidis, R. W. Boyd, E. Yablonovitch & X. Zhang, "Large spontaneous-emission enhancements in metallic nanostructures: towards LEDs faster than lasers." ***Optics Express***, 24, 16, 2016.	2016
290	H. Ramezani, Y. Wang, E. Yablonovitch & X. Zhang, "Unidirectional Perfect Absorber." ***IEEE Journal of Selected Topics in Quantum Electronics***, 22, 2016.	2016
289	P. K. Jha, M. Mrejen, J. Kim, C. Wu, Y. Wang, Y. V. Rostovtsev & X. Zhang, "Coherence-Driven Topological Transition in Quantum Metamaterials." ***Physical Review Letters***, 116, 2016.	2016
288	S. S. Kruk, Z. J. Wong, E. Pshenay-Severin, K. O'Brien, D. N. Neshev, Y. S. Kivshar & X. Zhang, "Magnetic hyperbolic optical metamaterials." ***Nature Communications***, 7, 2016.	2016

PT symmetric system example

Parity ($\mathbf{x} \rightarrow -\mathbf{x}$) Time reversal ($i \rightarrow -i$)

PT symmetric Hamiltonian: $(\mathrm{PT})H(\mathrm{PT}) = H$

$$H\phi_n = E_n\phi_n$$

$$H(\mathrm{PT})\phi_n = (\mathrm{PT})E_n\phi_n = \begin{cases} E_n(\mathrm{PT})\phi_n & \text{: PT-exact phase (real eigenvalue)} \\ E_n^*(\mathrm{PT})\phi_n & \text{: PT-broken phase (complex eigenvalue)} \end{cases}$$

(Example)

$$H = \begin{pmatrix} iV & g \\ g & -iV \end{pmatrix} \Longrightarrow E_\pm = \pm\sqrt{g^2 - V^2}$$

EP condition: $g = V$

- At an EP, transition between two phases occurs.

Unidirectional total transmission in PT symmetric system

Transfer matrix form: $\begin{pmatrix} A \\ B \end{pmatrix} = M \begin{pmatrix} C \\ D \end{pmatrix} = \begin{pmatrix} a^* & ib \\ -ic & a \end{pmatrix} \begin{pmatrix} C \\ D \end{pmatrix}$ and $\det(M) = 1$

(PT-symmetric: $M^{-1} = M^*$)

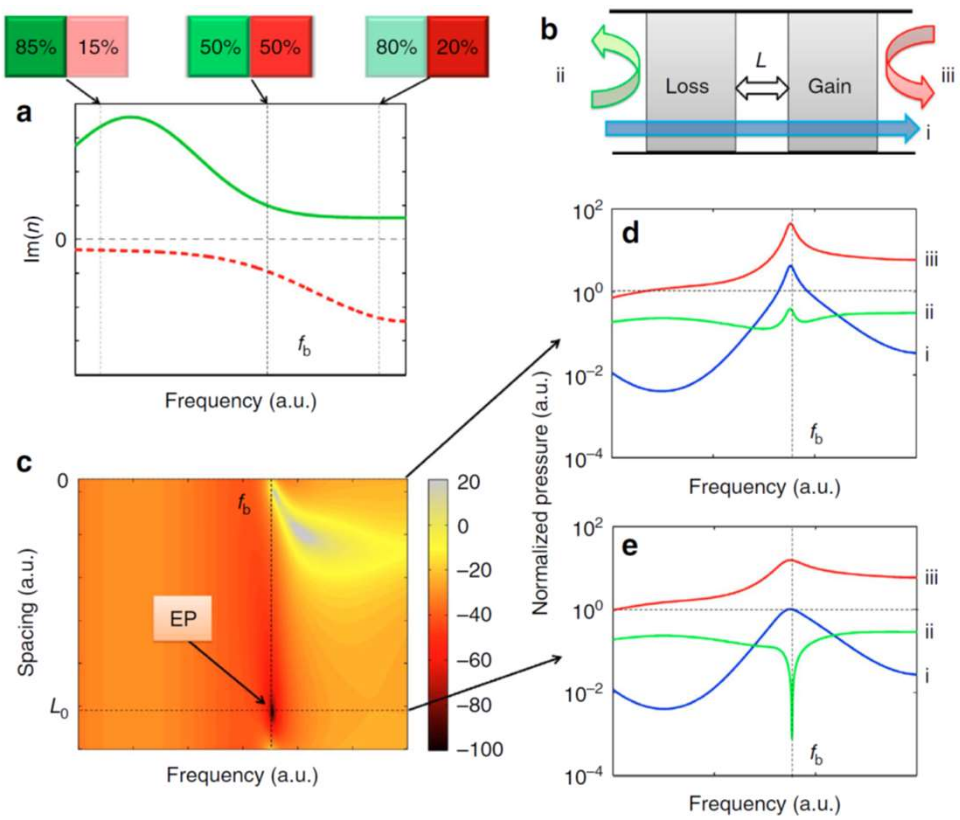
Scattering matrix: $\begin{pmatrix} D \\ A \end{pmatrix} = \frac{1}{a} \begin{pmatrix} 1 & ic \\ ib & 1 \end{pmatrix} \begin{pmatrix} B \\ C \end{pmatrix} = \begin{pmatrix} t & r_g \\ r_l & t \end{pmatrix} \begin{pmatrix} B \\ C \end{pmatrix} = S \begin{pmatrix} B \\ C \end{pmatrix}$

Eigenvalues of S: $\lambda = t \pm \sqrt{r_l r_g}$

At an EP of S matrix: $r_l r_g = 0$

➡ $r_l = 0$ or $r_g = 0$ (Unidirectional total transmission)

Exceptional points of acoustic PT symmetric structure



(a) Imaginary parts of the refractive indices of loss and gain materials with dispersion

(b) Loss and gain with spacing

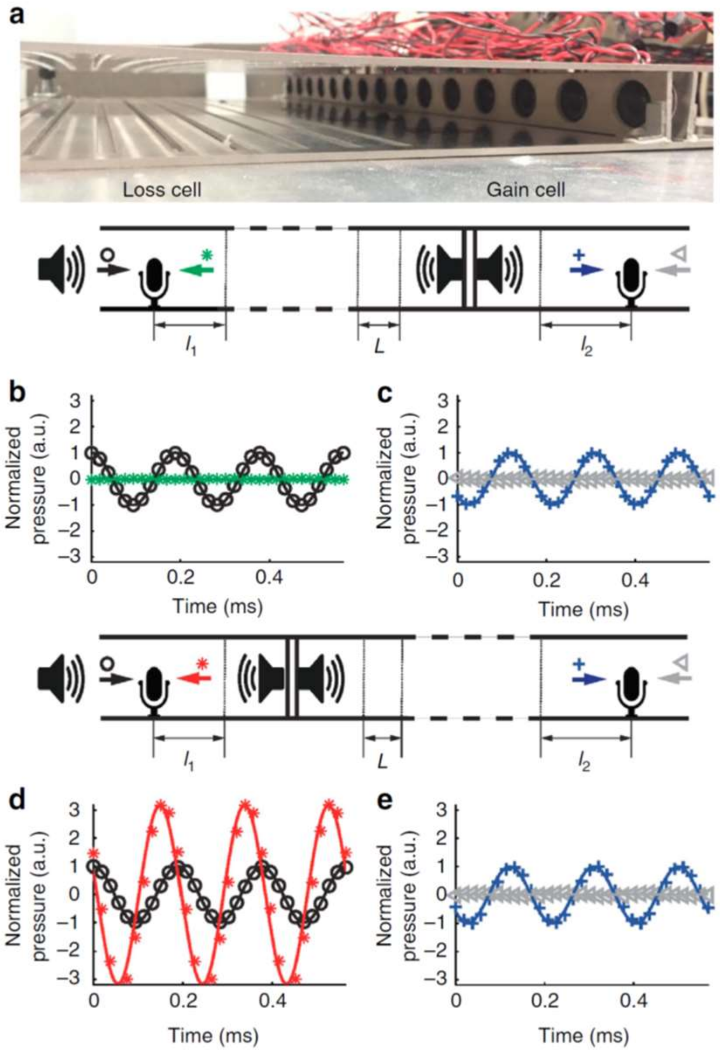
(c) Reflection from the loss side

(d) Normalized transmission (blue), reflection from the loss side (red), reflection from the gain side (green) with no spacing

(e) With spacing L_0 and an EP observed at f_b

- Gain and loss dispersion restrict the frequency range for an EP condition.
- Loss-gain spacing is necessary for accessing an EP.

Experimental demonstration of unidirectional transparency



$$|S| = \begin{pmatrix} |t_l| & |r_g| \\ |r_l| & |t_g| \end{pmatrix} = \begin{pmatrix} 0.99 & 3.34 \\ 0.02 & 1.02 \end{pmatrix}$$

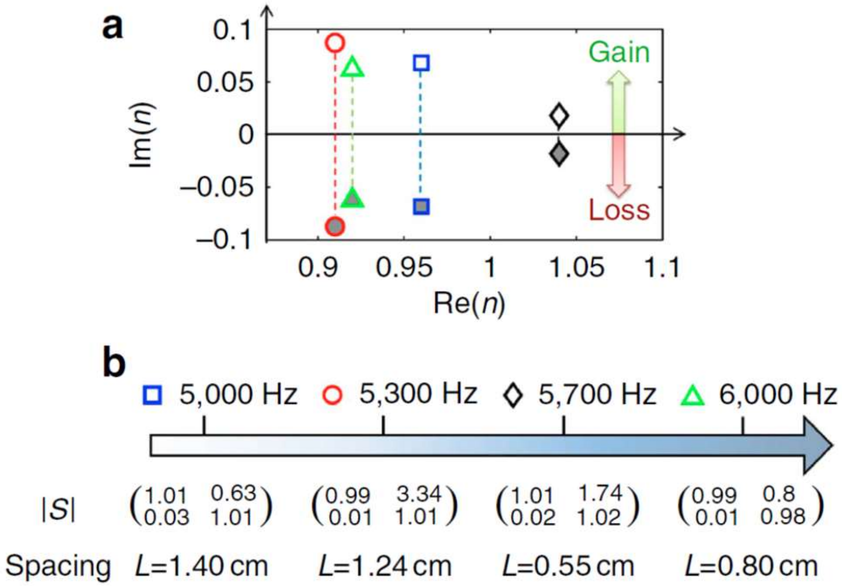
(a) Setup

(b), (c) Calculated (solid curves) and measured (marked dots) transmissions and reflections from the loss side with the spacing $L = 1.24cm$

(d), (e) Similar representation to (b) and (c) (from the gain side)

- First, obtain the scattering matrix of the loss part without gain unit at 5.3kHz.
- Obtain loss parameters from the S matrix.
- Obtain gain parameters by complex conjugation of loss parameters.
- Reverse process from parameter to scattering matrix.
- Loss and gain unit assembled with the correct spacing ➔ Unidirectional transparency

Accessing EPs at multiple frequencies

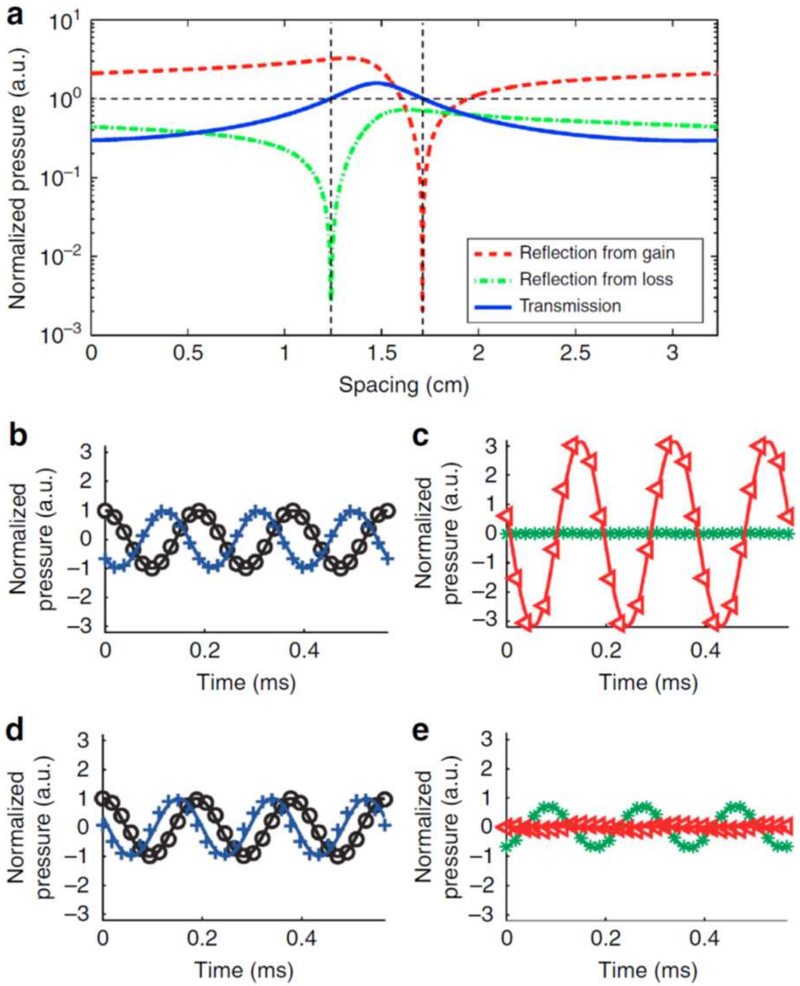


(a) Measured complex refractive indices of the loss and gain materials

(b) Measured scattering matrices for the controlled EPs at four frequencies

- Applying opposite phase shifts to the acoustic source array in gain unit introduce an effective spacing between gain and loss unit.
- By tuning the effective spacing, accessing EPs at multiple frequencies is possible.

Reversing the unidirectional transparency



(a) Calculated transmission (blue) and reflections from the gain (orange) and the loss side (green) with varying the spacing.

(b), (c) Transmission and reflections from the gain and loss side with 1.24cm-spacing
(black: incidence, blue: transmission, red: reflection from loss side, green: reflection from gain side)

(d), (e) Transmission and reflections from the gain and loss side with 1.71cm-spacing

- $r_l r_g = 0$ at an EP reveals that two types of EPs exist depending on the side of where reflection is cancelled.
- Orientation of the unidirectional transparency can be controlled by tuning the spacing between the loss and gain.

Summary

- Unidirectional transmittance at an EP in a PT-symmetric acoustic system demonstrated.
- Restriction of EP frequency due to the dispersion was overcame by tuning the spacing between the loss and gain media.
- Direction of the total transmission can be switched also by the loss-gain spacing.
- Can be applied to isolators, diodes, rectifiers…