Broadband Coherent Perfect Absorption in Chiral Photonic Systems

Abe Bradley†, William Tuxbury†, and Tsampikos Kottos†

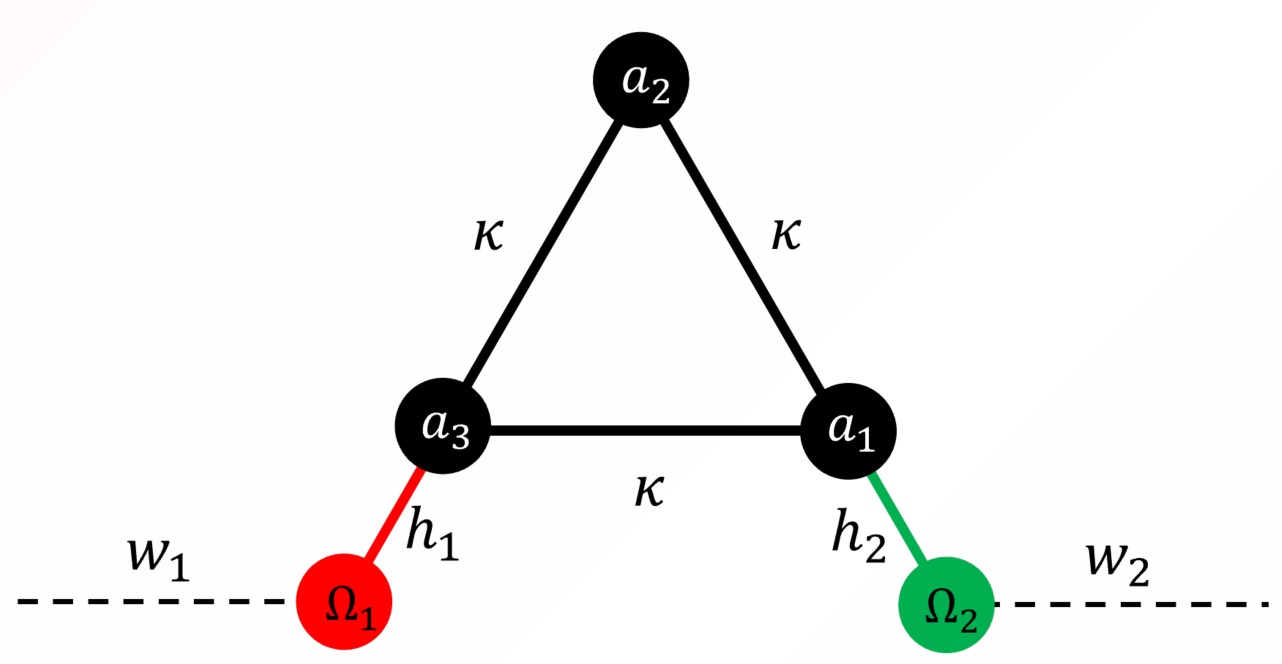
†Wave Transport in Complex Systems Group, Physics Department, Wesleyan University, Middletown, CT 06459, USA

Introduction

Coherent perfect absorption (CPA) is a steady-state process in which a lossy cavity completely absorbs the energy from an incident wavefront. The phenomenon can be understood as a time reversed lasing: rather than gain induced emission in the absence of driving, CPA results from loss induced destructive interference. Such a delicate process is often assumed to only be achievable for a particular wavefront operating at a specific frequency. Despite this obstacle, it has recently been demonstrated that a broadened CPA linewidth is possible in chiral exceptional point (CEP) systems. In systems where chirality of modes can be established, such as in a microring resonator, operating in the vicinity of an EP induces a chiral wave propagation with handedness associated with the coalescing eigenstates. At the exceptional point, the chirality is reversed, and the wave propagates unidirectionally with handedness given by the Jordan vector, which is opposite to that of the degenerate eigenstate.

To realize a chiral coherent perfect absorption, we use a 1-port discrete photonic ring array with two additional lossy scatterers, where we balance the resonant frequency and loss of these scatterers such that the system operates at an EP. The lossy sites serve to modulate destructive interference, inducing a unidirectional coupling between the propagating and counter-propagating modes of the ring, hence providing a platform to realize a broadband CPA-CEP.

Coherent Perfect Absorption



Scattering Matrix:

$$S(k) = -1 + 2i\,\frac{\sin k}{\kappa_l}\,W^T \frac{1}{\omega(k) - H_{eff}(k)} W \quad ; \quad W = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ w_1 & 0 \\ 0 & w_2 \end{pmatrix}$$

$$H_{eff}(k) = H - \Lambda(k)\ , \quad \Lambda(k) = \frac{e^{ik}}{\kappa_l} W W^T$$

S-Matrix Zeros:

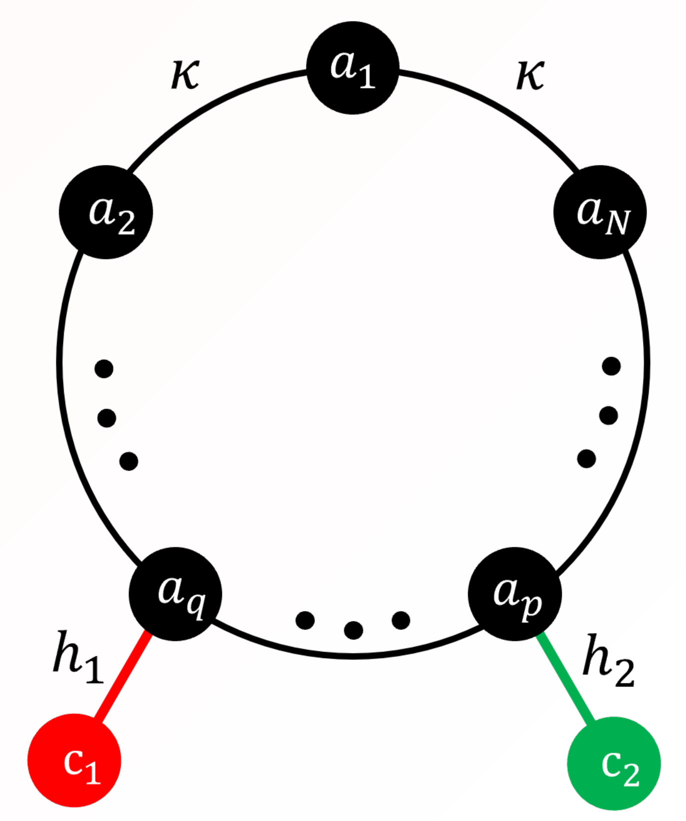
$$\det[S] = \frac{\det[\omega - H_{eff}(-k)]}{\det[\omega - H_{eff}(k)]} \longrightarrow \det[S] = 0 = \det[\omega - H_{eff}(-k)]$$

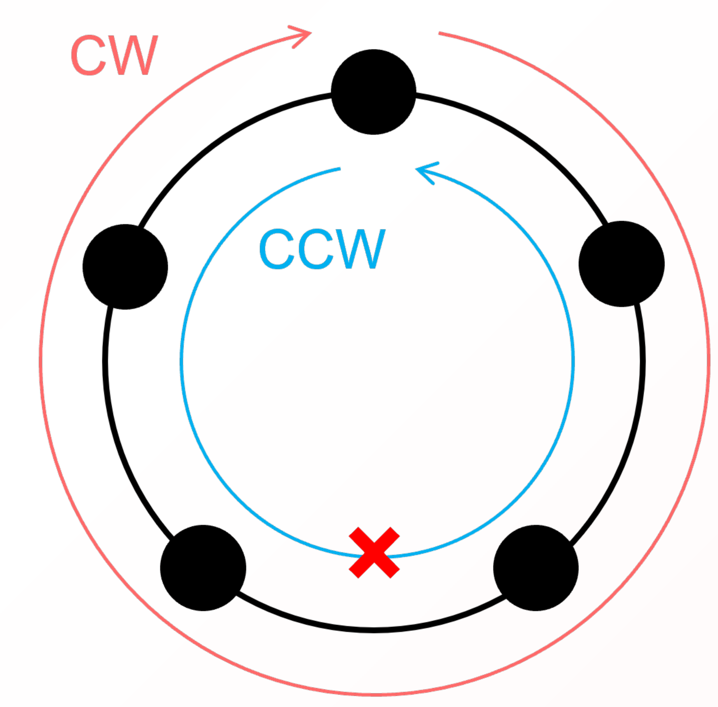
Wideband Approximation:

$$S(\omega) = -1 + 2i\,W^T \frac{1}{\omega - H_{eff}} W \quad ; \quad H_{eff} = H - \Lambda\,,\ H_{dual} = H + \Lambda\,,\ \Lambda = i\,W W^T$$

$$\det[S] = \frac{\det[\omega - H_{dual}]}{\det[\omega - H_{eff}]} \longrightarrow \det[S] = 0 = \det[\omega - H_{dual}]$$

Chirality in a Discrete Photonic Ring Array





Coupled Mode Theory (CMT) System Description:

$$\begin{cases} i\dfrac{da_n}{dt} = \omega_0 a_n + \kappa a_{n-1} + \kappa a_{n+1} + \delta_{n,p} h_1 c_1 + \delta_{n,q} h_2 c_2 \\ i\dfrac{dc_1}{dt} = \Omega_1 c_1 + h_1 a_p \\ i\dfrac{dc_2}{dt} = \Omega_2 c_2 + h_2 a_q \end{cases} \quad ; \quad k_m = \frac{2m\pi}{N} \qquad \mu_m = \omega_0 + 2\kappa\cos(k_m)$$

Mode Space System Description:

$$\begin{cases} i\frac{dA_m}{dt} = \mu_m A_m + \left[\frac{h_1^2}{N\Delta_1} + \frac{h_2^2}{N\Delta_2}\right] A_m + \left[\frac{h_1^2}{N\Delta_1} e^{-2ik_m p} + \frac{h_2^2}{N\Delta_2} e^{-2ik_m q}\right] A_{m'} \\ i\frac{dA_{m'}}{dt} = \mu_m A_{m'} + \left[\frac{h_1^2}{N\Delta_1} + \frac{h_2^2}{N\Delta_2}\right] A_{m'} + \left[\frac{h_1^2}{N\Delta_1} e^{2ik_m p} + \frac{h_2^2}{N\Delta_2} e^{2ik_m q}\right] A_m \\ i\frac{dA_\eta}{dt} = \mu_\eta A_\eta + \left[\frac{h_1^2}{N\Delta_1} + \frac{h_2^2}{N\Delta_2}\right] A_\eta \end{cases} \quad ; \quad h_j^2 \ll \Delta_j \ll 1 \qquad \eta \in \left\{0, \frac{N}{2}\right\}\ ,\ m, m' \neq \eta$$

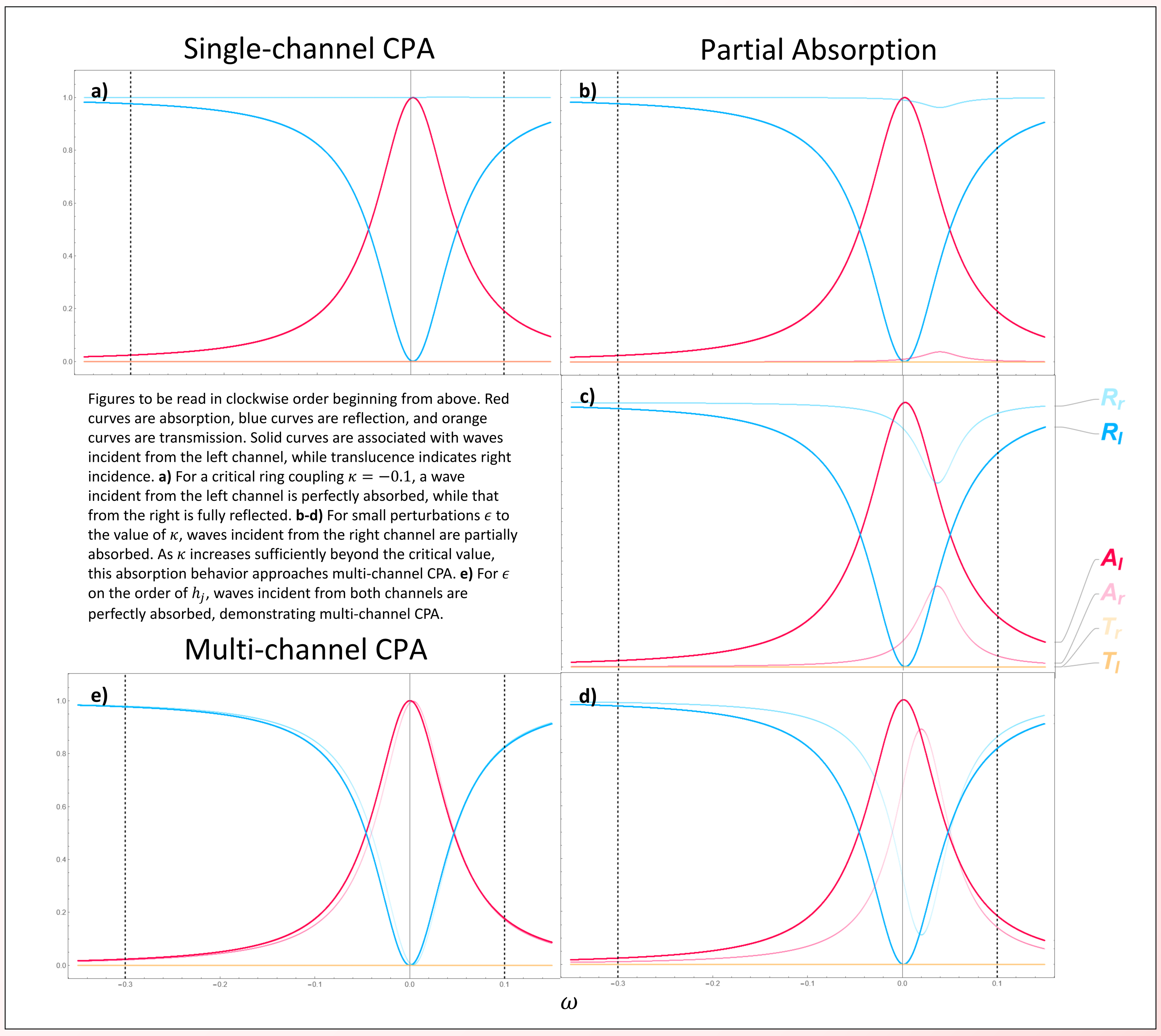
Chirality Conditions:

$$\frac{h_j^2}{N\Delta_j} \equiv \chi e^{i\phi_j} \quad , \quad \Delta\phi = \phi_2 - \phi_1$$

$$\begin{cases} \Delta\phi = [b + \theta]\pi \\ \theta = \dfrac{4m(q-p)}{N} \end{cases} \quad ; \quad b \in 2Z + 1$$

Suboptimal Unidirectionality: $N \neq 1, 2, 4 \quad ; \quad \theta \notin Z$

Optimal Unidirectionality : $N \in 8Z \quad ; \quad \theta \in Z + \frac{1}{2}$



Figures to be read in clockwise order beginning from above. Red curves are absorption, blue curves are reflection, and orange curves are transmission. Solid curves are associated with waves incident from the left channel, while translucence indicates right incidence. **a)** For a critical ring coupling $\kappa = -0.1$, a wave incident from the left channel is perfectly absorbed, while that from the right is fully reflected. **b-d)** For small perturbations ϵ to the value of κ, waves incident from the right channel are partially absorbed. As κ increases sufficiently beyond the critical value, this absorption behavior approaches multi-channel CPA. **e)** For ϵ on the order of h_j, waves incident from both channels are perfectly absorbed, demonstrating multi-channel CPA.

Acknowledgements

I would like to acknowledge the support of my graduate mentor William Tuxbury, as well as the professorial mentorship of Tsampikos Kottos. Additionally, the following have been used in the development of the ideas presented here:

1. Yan V Fyodorov, Suwun Suwunnarat, and Tsampikos Kottos. Distribution of zeros of thes-matrix ofchaotic cavities with localized losses and coherent perfect absorption: non-perturbative results.Journalof Physics A: Mathematical and Theoretical, 50(30):30LT01, Jun 2017.
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4. William R. Sweeney, Chia Wei Hsu, Stefan Rotter, and A. Douglas Stone. Perfectly absorbing exceptionalpoints and chiral absorbers.Physical Review Letters, 122(9), Mar 2019.