Radiation control with exceptional points in non-Hermitian plasmonic systems

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Abstract

In this paper, we introduce our research based on the singular eigenstates in EP. The first is formation of circular polarization eigenstates and the second is formation of Huygens dipoles at EPs. The studies introduced in this paper provide new photonic functionalities caused by the singular eigenstates at EP in NH systems.

1. Introduction

In recent years, the physics of systems described by non-Hermitian (NH) Hamiltonians has attracted a great deal of attention from researchers. The NH systems with PT symmetry exhibit PT phase transition from PT symmetric phase to PT broken phase across exceptional point (EP). The eigenvalues and eigenmodes coalesce at the EP, which is very unique property of NH system with PT symmetry [1].

Since photonic systems are naturally described by NH Hamiltonian due to radiation loss and material gain/loss, many photonic systems involving NH photonics have been reported and shown variety of intriguing phenomena [2].

So far, many studies have been reported on NH photonics, but only a few have focused on the phenomena occurring directly at the EP [3]. Especially, few studies have focused on *singular eigenstates* with $\pm\pi/2$ phase difference.

In this paper, we introduce our research focusing on *the singular eigenstates* in EP. The first is formation of circular polarization eigenstates [4] and the second is formation of Huygens dipoles [5] at EPs. The studies introduced in this paper provide new photonic functionalities caused by the singular eigenstates at EP in NH systems.

2. Singular eigenstate at EP

The simplest example of photonic systems described by NH Hamiltonian with PT symmetry is coupled two resonators described by 2x2 matrix as follows,

$$\mathcal{H} = \begin{pmatrix} i\gamma & \kappa \\ \kappa & -i\gamma \end{pmatrix}.$$

Here, γ is loss/gain rate of resonators and κ is a coupling constant. Eigenfrequency and eigenstates of the Hamiltonian are

$$\omega_{\pm} = \pm\sqrt{\kappa^2 - \gamma^2}$$

and

$$\begin{pmatrix} 1 \\ \dfrac{-i\gamma \pm \sqrt{\kappa^2 - \gamma^2}}{\kappa} \end{pmatrix}.$$

When $\kappa = \gamma$, the eigenvalues and eigenstates coalesce, which means only one mode can exist in spite of a coupled two resonator system. The singularity point is called an EP in NH systems. The eigenstate at EP can be written as,

$$\begin{pmatrix} 1 \\ -sign(\kappa)i \end{pmatrix},$$

which means the relative phase difference between two resonators is $\pm\pi/2$ and the sign is determined by the sign of the coupling constant κ. In this study, we investigate physical phenomena induced by the singular eigenstate with $\pm\pi/2$ phase difference in photonic systems.

3. Circular polarization eigenstates at EP

First, we introduce switchable polarization eigenstates in a NH plasmonic system by using GST phase transition. we discuss about circular polarization eigenstates induced by singular eigenstates at EP in Jones matrix [3]. Figure 1(a) shows the proposed coupled plasmonic resonators. Although the x- and y-bars cannot couple due to the symmetry in the case of $d_x = 0$ nm, symmetry breaking due to the shift d_x induces the coupling between the bars and coupling strength can be controlled through the value of d_x.

To achieve the system described by a NH matrix with (passive) PT symmetry, GST is put at the one end of the y-bar as an additional loss material (Fig. 1(a)), which introduces loss contrast between the x- and y-bars (difference in imaginary parts of diagonal terms). At 1.5 μm, crystal phase GST has finite loss while material loss is negligible in amorphous phase. Therefore, the system described by a NH matrix with (passive) PT symmetry is realized only by crystal phase GST. Once GST phase is changed to amorphous, the system becomes the system described by usual Hermitian matrix, which suggests that GST phase transition is applicable to reconfigurable NH photonic systems at near infrared frequency region.

Figure 1(b) shows trajectories of the polarization eigenstate derived from Jones matrix on Poincaré sphere in the case of crystal GST. As the shift d_x increases, two polarization eigenstates move from x-, y- polarization to ±45-degree polarization. Importantly, two polarization eigenstates approach the same pole (left-circular polarization), which indicates PT phase transition through the EP occur in polarization space. The circular polarization eigenstate corresponds to the singular eigenstate (1, i) at EP in x, y basis. Therefore, the proposed plasmonic system loaded by crystal GST can be described by NH matrix with loss biased PT symmetry.

Figure 1(c) shows the trajectories for amorphous GST. In contrast to the results of crystal GST, the trajectories are always on the equator of the Poincaré sphere, which means polarization eigenstates are linear polarization regardless of the coupling strength. The results show that the system is described by usual Hermitian matrix because of negligible loss of amorphous GST. By using crystal-amorphous phase change of GST, polarization eigenstates can be switched from elliptical to linear polarization.

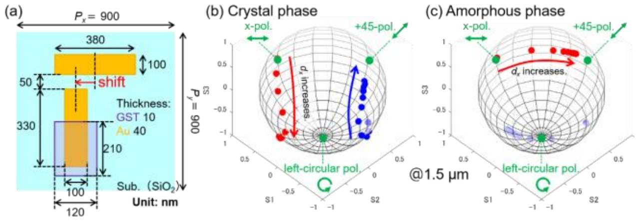

Figure1: (a) A schematic of the proposed structure. Trajectories of polarization eigenstates on Poincaré sphere for (b) crystal and (c) amorphous phases.

4. Huygens dipole formation at EP

Next, we introduce formation of Huygens dipole by the coupled SRRs described by NH Hamiltonian due to the difference in radiation losses. Huygens dipole is defined as a combination of electric and magnetic dipoles which arranged orthogonally each other [6]. Radiation fields from a Huygens dipole survives at only one direction and the radiation to the opposite direction is eliminated by destructive interference. Therefore, unidirectional radiation can be achieved by formation of Huygens dipole in artificial structures.

In order to mimic electric and magnetic dipoles in artificial structures, induced electric and magnetic dipoles in a split ring resonator (SRR) at the lowest resonance are employed (Fig. 2(a)). Different gap orientations of SRRs makes the system NH. Since phase of electric and magnetic dipoles are initially different by $\pi/2$, 0 or pi phase difference, which is necessary for Huygens dipole, can be obtained at the singular eigenstates with $\pi/2$ phase difference at EPs.

By sweeping geometrical parameters, we can observe two EPs, which is manifested by self-intersecting Riemann surface structure in complex eigenfrequencies (Fig. 2(b)). These EPs correspond to singular eigenstates by positive and negative coupling constants. We expect that unidirectional radiation due to the formation of Huygens dipoles should be observed at two EPs. To confirm this, we plot z-components of Poynting vector Pz at upper and lower surfaces of simulated models as shown in Fig. 2(c). Black arrows indicate direction and amplitude of Poynting vector in a log scale. Clear unidirectionality is observed at EP1 and EP2, which support the formation of Huygens dipoles. Furthermore, the radiation direction reverses between EP1 and EP2, meaning that the sign of the coupling constant flips from negative to positive.

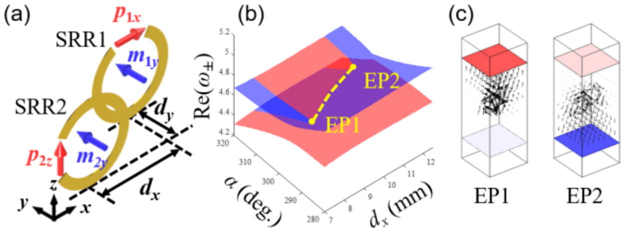

Figure2: (a) A schematic of the proposed structure. (b) Real eigen frequency surfaces for the coupled system. (c) Poynting vector flows at EPs.

5. Summary

In this study, we introduced photonic phenomena induced by singular eigenstates at EPs in NH systems. The singular eigenstate with $\pi/2$ phase difference is unique property of EP in NH system, which can not be achieved in usual Hermitian coupled systems. First, we proposed and numerically investigated the switchable polarization eigenstates in the NH plasmonic system by using GST phase transition. The loss contrast was introduced by adding crystal GST, and PT phase transition through the singular eigenstate at EP was demonstrated. Moreover, crystal-amorphous phase change of GST realized the switching of the polarization eigenstates from elliptical to linear polarization. Next, we theoretically and numerically investigated the coupled SRRs described by NH Hamiltonian due to the difference in radiation losses. Unidirectional radiation was observed at singular eigenstates at EPs, which support the formation of Huygens dipoles. Furthermore, the radiation direction reversed between EPs, meaning that the sign of coupling constats flip from negative to positive. The photonic functionalities originating from singular eigenstates at EPs would pave the way to realize reconfigurable NH based photonic devices.

Acknowledgements

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