Nonlinearity Controlled Asymmetric Mode-Conversion in an Optical Waveguide Hosting an Exceptional Point

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1. Introduction

Exceptional points (EPs) are the topological singularities in open quantum/ wave systems where at least two coupled states coalesce [1-3]. A dynamically encircled EP with time (or length) dependent parametric distribution and associated adiabatic breakdown in the modal dynamics offers a unique light manipulation tool in the context of asymmetric mode conversion [1-3]. Here depending on the chirality of the device and owing to the associated nonadiabatic corrections around EP, light is converted to a specific dominating mode, irrespective of the choice of input mode [1-3]. In this paper, we report a gain-loss assisted dual-mode optical waveguide that hosts a parameter space to encircle an EP dynamically. With the onset of saturable nonlinearity in the spatial index distribution of the waveguide, we investigate the nonreciprocal light dynamics below the isolation limit and study an interplay between the conversion efficiencies during EP-aided asymmetric-mode-conversions and the amount of optical nonlinearity in the optical medium.

2. Design of the optical waveguide and results

Normalizing the operating frequency $\omega = 1$, we configure an optical waveguide having the core and cladding refractive index n_h and n_l, respectively, as described in Fig. 1(a); where we set the total width $W = 40$ and operating length $L = 10^4$ (in a dimensionless unit). Designed waveguide hosts only the fundamental mode (ψ_0) and the first higher order mode (ψ_1). To study the nonreciprocal light dynamics through the waveguide, we introduce saturable nonlinearity (n_{NL}) [4] in the optical medium; where the nonlinearity level is quantified by $\Delta n_{NL} = (n_{NL}/\Delta n) \times 100\%$ with $\Delta n = (n_h - n_l)$. The supported modes are coupled with a spatial distribution of inhomogeneous gain-loss profile that is characterized by two independent parameters gain-coefficient (γ) and loss-to-gain ratio (τ). Now, tuning γ and τ, we numerically locate an EP in (γ, τ)-plane at ~ (0.008, 3.161), which is being dynamically encircled with the chosen parameter plane as shown in Fig. 1(b.1). The corresponding length dependent gain-loss distribution is shown in Fig. 1(b.2). Now, introducing 0.1% nonlinearity, we study the mode-propagations in Fig. 1(c). For clockwise EP-encirclement process, during propagation of ψ_0 and ψ_1 along the forward direction, both of them are converted to ψ_1 (upper panel) with conversion efficiencies $C_F = 72.5\%$. Now, when we consider anticlockwise EP-encirclement process, then during propagation along the backward direction, both of them are converted to ψ_0 (lower panel) with conversion efficiencies $C_B = 76.7\%$. Here, conversion efficiencies during such asymmetric-mode-conversions are calculated using overlap integrals between input and output modes [1-2].

In presence of nonlinearity, the waveguide allows the bi-directional light propagation only below the isolation limit. So, tuning Δn_{NL} up to a certain limit, we can control the mode conversion efficiencies (C_F and C_B); which is exclusively reported in Fig. 1(d). As can be seen in Fig. 1(d.1) and (d.2), C_F increase gradually up to 98%, whereas C_B increases up to 78%, respectively, with an increasing Δn_{NL} up to 1%. As the lower average loss during light propagation in the forward direction results in better control of the relative gain of the supported modes, in presence of nonlinearity, the increasing rate of C_F is comparably high in comparison with C_B. A saturating trend has been observed near $\Delta n_{NL} =$ 0.9% for both the cases, however, a further increase in nonlinearity above 1% will reach the isolation limit, and then the light will be allowed to pass in any of the one direction.

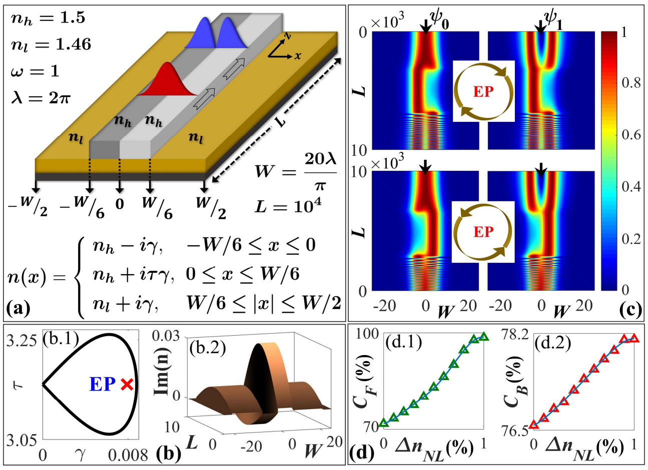

Fig. 1: (a) Schematic of the proposed waveguide with operating parameters and transverse refractive index profile. **(b)** (b.1) Parametric variation in (γ, τ)-plane and (b.2) corresponding length dependent gain-loss distribution to encircle an embedded EP dynamically. (c) Propagation of ψ_0 and ψ_1 with 0.1% nonlinearity; where both the modes are converted to ψ_1 (upper panel) for clockwise EP-encirclement and ψ_0 (lower panel) for anticlockwise EP-encirclement process. (d) Variation of (d.1) C_F and (d.2) C_B with an increasing Δn_{NL}, below the isolation limit.

3. Conclusion

In summary, introducing nonlinearity within the isolation limit, we report an exclusive way to control EP-aided asymmetric mode conversions; which opens up a unique possibility to control light flow in integrated devices.

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