Theory of Exceptional Points of Degeneracy in Coupled Waveguides With Balanced Gain and Loss

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We present a unified theory of exceptional points of degeneracy (EPD) in coupled-mode guiding structures, i.e., a theory that illustrates the electromagnetic mode characteristics under the special dispersion degeneracy condition of state eigenvectors. In particular, we investigate degeneracies of second and fourth orders in guiding systems modeled by two coupled transmission lines (CTLs). We show for the first time the concept of Parity-Time (PT)-symmetry in coupled uniform transmission lines with balanced and symmetric gain-loss and how this condition is associated with a second order EPD. Fourth order degeneracies in periodic couple waveguides are also demonstrated, namely the degenerate band edge (DBE) in both lossless and gain-loss balanced structures. Importantly, we determine how the disorder or perturbations, such as imperfect coupling, symmetry breaking or presence of unbalanced gain/losses, affect the EPDs. Using our developed figure of merit, a quantitative assessment of EPD can be established since practical realizations of waveguides with EPD are highly prone to tolerance and disorders. We also show how such fourth order EPD is perturbed due to tolerances and losses using full-wave simulation and demonstrate that experimentally as well in a metallic waveguide with DBE. We show that by introducing gain into naturally lossy structures provides for (i) the conditions whereby exceptional points of non-Hermitian degeneracies can be manifested, such as in PT-symmetric structures, or (ii) to compensate the losses for deteriorated degeneracies, such as in DBE structures with gain and loss. In this paper we show examples of EPDs at RF and microwave frequencies in coupled microstrip line technology as well as slow-wave structure for high power applications. These special degeneracy conditions are promising to enhance the performance of a variety of microwave and optical resonators and devices such as oscillators, including lasers, amplifiers and sensors.