

**Simulation of the effects of geometry and gain loss control on dynamic gain and EP optical frequency comb in a exceptional point laser.**

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**Abstract.** Exceptional points (EPs) are branch-point singularities in non-Hermitian systems where eigenvalues and eigenvectors coalesce [1]. Microcavity lasers enable fine control of gain and loss, making them an ideal platform for steady-state EP operation and EP-enabled functionalities such as enhanced sensing, mode selectivity, and chiral emission. Recent work shows [2], near an EP, two nearly degenerate modes in a semiconductor laser produce gain-followed beating that dynamically modulates the carrier inversion, enabling spontaneous OFC generation above threshold. EP OFC has a repetition rate not constrained by the cavity free spectral range, enabling wide repetition-rate tunability in a compact cavity. Moreover, once the pump exceeds threshold, it can self-start without an external modulator or a continuous-wave seed laser. Here, we use the open-source Periodic-Inversion Ab Initio Laser Theory (PALT) to analyze lasing thresholds and the existence/stability of OFC solutions, and to show how DFB/DBR-like parameters control EP proximity and the comb-generation window.

**The main part.** We study a one-dimensional gain–loss coupled cavity composed of three DBR sections, with an active gain segment and a lossy segment inserted in the middle. The pump profile is Gaussian, with a peak value  $D_{\max}$ , and  $\sigma/\epsilon_0$  characterizes the absorption segment. Our study consists of three parts.

Part I: We compute the first threshold  $D_{\text{th1}}$  and scan EP-controlling parameters: DBR pair number/duty cycle, passive-cavity length  $L_2$ , and pump  $D_{\max}$ . Small  $L_2$  perturbations induce large eigenvalue shifts in the complex-frequency plane. Asymmetric DBR duty cycles strongly modify coupling and effective loss.

Part II: We compute the second threshold  $D_{\text{th2}}$  via PALT stability analysis. The criterion  $\text{Im}(\omega_1)=0$  indicates loss of single-mode stability at  $\omega_0$  and the onset of a second oscillating mode, marking the start of frequency-comb formation.

Part III: For  $D_{\max}$  above  $D_{\text{th2}}$ , we compute the PALT limit-cycle solution with periodic inversion (EP-OFC). This computation is highly initialization-sensitive. Within converged solutions, we observe that  $D_{\max}$  mainly controls the overall comb-tooth height, while  $\sigma/\epsilon_0$  controls the outer-envelope width and the number of sustained comb lines. Finally, using the converged limit-cycle fields, we reconstruct spatial intensity profiles for individual comb lines, and provided insight into how EP-related modal coalescence and cavity design jointly shape the OFC spectrum.

**Conclusions.** We studied OFC formation in a gain–loss coupled DBR cavity near an EP using PALT. By scanning DBR duty cycles/pair numbers, passive-cavity length  $L_2$ , and pump level  $D_{\max}$ , we tracked two complex eigenfrequencies to identify EP-proximate regimes with minimized splitting. We computed  $D_{\text{th1}}$  and determined a unique  $D_{\text{th2}}$  from the PALT stability condition  $\text{Im}(\omega_1) = 0$ , mark the loss of single-mode stability and the onset of multimode dynamics. For  $D_{\max} > D_{\text{th2}}$ , PALT yields limit-cycle solutions and an EP-enabled OFC with equidistant lines;  $D_{\max}$  mainly sets the overall comb level, while  $\sigma/\epsilon_0$  controls the comb width and the number of sustained lines. We also reconstructed spatial profiles of selected comb lines. It provides guidance for further cavity optimization. Future work will map the joint parameter space of EP proximity and comb stability, and will extend the model toward experimentally realistic semiconductor gain and fabrication tolerances.

**References:**

[1] Miri M A, et al. Exceptional points in optics and photonics[J]. Science, 2019, 363(6422): eaar7709.

[2] Gao, Xingwei, et al. "Dynamic gain and frequency comb formation in exceptional-point lasers." *Nature Communications* 15.1 (2024): 8618.