Optical amplification at exceptional points

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Abstract: We propose a new optical amplifier geometry based on exceptional points. Compared to its standard counterpart device, the proposed structure relaxes the limitation imposed by the gain-bandwidth product.

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Signal amplification is one of the most fundamental processes in optical science and engineering. Optical amplifiers (OAs) can be classified into traveling [1] or standing [2] waves devices. The former offers a larger bandwidth at the expense of the attainable gain values. On the other hand, the latter can have larger gain due to the power recycling in the resonator, allowing for a smaller device size. However, the resonant condition leads to a very narrow bandwidth. This fundamental limitations pertinent to cavity-based optical amplifiers is known as the gain-bandwidth product.

Here we introduce a new OA scheme based on optical resonators operating at exceptional points (EPs) – a special type of singularities at which two or more eigenstates coalesce [3,4]. We show that the gain-bandwidth product of the proposed device scales differently from that of standard resonators, which leads to superior performance.

The proposed structure consists of a microring resonator coupled to two identical waveguides, one of which is terminated by a mirror, as shown in Fig. 1(a). Optical gain g is applied to the ring where the amplification process takes place. In the absence of any excitation, the above system is described by the following effective Hamiltonian [5]:

$$i\frac{d}{dt}\begin{bmatrix} a_{\text{cw}} \\ a_{\text{ccw}} \end{bmatrix} = H \begin{bmatrix} a_{\text{cw}} \\ a_{\text{ccw}} \end{bmatrix}, \quad H = \begin{bmatrix} \Omega & 0 \\ -2i\gamma r e^{i\phi} & \Omega \end{bmatrix} \tag{1}$$

Here r is the magnitude of the field reflection coefficient of the mirror, $\Omega = \omega - \omega_0 - i(2\gamma + \alpha - g)$ where ω and ω_0 are the input signal angular frequency and resonant frequency, respectively. Additionally, α and γ are the decay rates due to radiation/material loss, and coupling to waveguides, correspondingly. The Hamiltonian H is a non-diagonalizable

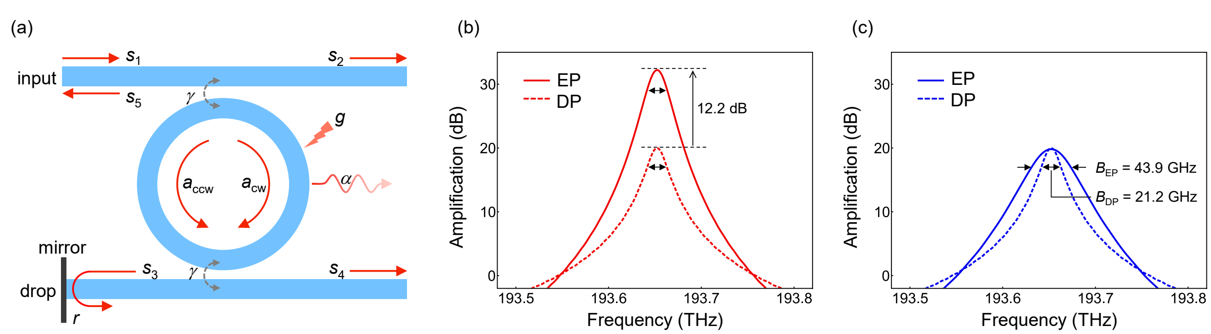

Fig. 1. (a) A schematic of the proposed structure for an optical amplifier working at an EP that arises from the unidirectional coupling from the clockwise (CW) mode a_{cw} to the counterclockwise (CCW) mode a_{ccw}. (b) and (c) present a comparison between the proposed EP-based amplifier and a standard device (without the mirror) for fixed bandwidth or gain), respectively. Evidently, the EP-based OA demonstrates better performance.

Jordan matrix that features an EP [6]. By using the coupled mode theory, we obtain the scattering coefficient between the input and output ports:

$$s_{51} \equiv \frac{s_5}{s_1} = \frac{4re^{i\phi}\gamma^2}{[i(\omega-\omega_0)+2\gamma+\alpha-g]^2} \tag{2}$$

Note that this expression is valid only below the lasing threshold $g = 2\gamma+\alpha$. The maximum value of the amplification (at resonance) is $G_{\mathrm{EP}} \equiv \max[|s_{51}(\omega_0)|^2] = 16r^2\gamma^4/(2\gamma+\alpha-g)^4$. On the other hand, the bandwidth is given by $B_{\mathrm{EP}} = 2F(2\gamma+\alpha-g)$ with $F = \sqrt{\sqrt{2}-1}$. Compared to amplifiers based on diabolic points (DPs) that arise from Hermitian degeneracies, the bandwidth is reduced by a factor of F, while the gain is enhanced according to the quadratic relation $G_{\mathrm{EP}} = r^2 G_{\mathrm{DP}}^2$. This leads to the following expression for the gain-bandwidth product for the OA operating at an EP:

$$\chi_{\mathrm{EP}} \equiv \sqrt[4]{G_{\mathrm{EP}}} \cdot B_{\mathrm{EP}} = 4F\sqrt{r}\gamma \tag{3}$$

Equation (3) shows that the gain-bandwidth product for the EP regime scales differently than the case of DP, in which $\chi_{\mathrm{DP}} = \sqrt{G_{\mathrm{DP}}} \cdot B_{\mathrm{DP}} = 4\gamma$.

To demonstrate the advantage of the proposed amplifier operating at an EP, we compare its performance with DP-based amplifier in two different situations: (1) When they both share the same bandwidth but have different maximum amplification; and (2) When they both exhibit the same maximum amplification but have different bandwidth. In both cases, we take $r \approx 1$. In the first scenario, we fix the bandwidth by choosing the pump values to be $\tilde{g}_{\mathrm{EP}} = F^{-1}\tilde{g}_{\mathrm{DP}} + 2(1-F^{-1})$, where $\tilde{g} = (g-\alpha)/\gamma$. In our simulations, we used the same values for α but different gains γ. Under these conditions, the amplification enhancement is $G_{\mathrm{EP}}/G_{\mathrm{DP}} = 4F^4/(2-\tilde{g}_{\mathrm{DP}})^2$. Similarly, in the latter case, the bandwidth enhancement factor (for fixed maximum amplification) is $B_{\mathrm{EP}}/B_{\mathrm{DP}} = \sqrt{2}F/\sqrt{2-\tilde{g}_{\mathrm{DP}}}$ and the required pumping is $\tilde{g}_{\mathrm{EP}} = 2-\sqrt{2(2-\tilde{g}_{\mathrm{DP}})}$. Note that the EP-based OAs delivers a better performance only when $\tilde{g}_{\mathrm{DP}} > 2\sqrt{2}F^2 \approx 1.17$.

To confirm these predictions and explore realistic implementations, we consider a semiconductor-based optical structure having the following physical parameters: waveguide width w = 0.25 μm (for both the straight and the ring waveguides), ring radius R = 5 μm, edge-to-edge distance between the ring and either waveguides d = 0.15 μm. To implement the mirror, we assume a thin layer of silver with thickness of 100 nm. The material refractive index is $n_1 = 3.47$ (relevant to Si and AlGaAs implementations) and the background index is taken to be $n_2 = 1.44$ (silica for example). Figure 1 (b) and (c) present the comparison between the proposed EP-based amplifier and the standard device when DP $= 1.8$, where the clear advantage of the former is evident.

In conclusion, we have introduced a new design paradigm for optical amplifiers based on Jordan exceptional points. An important feature of the proposed structure is the unique scaling of its gain-bandwidth product which is different from standard amplifiers, and allows for achieving more gain or larger bandwidth of operation.

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