First-order all-optical spectral phase transition from coupled optical parametric oscillators

Arkadev Roy[1]**, Carsten Langrock**[2]**, Martin Fejer**[2]**, Alireza Marandi**[1]

[1] *Electrical Engineering Department, California Institute of Technology, Pasadena, California, 91125,USA*
[2]*Edward L. Ginzton Laboratory, Stanford University, Stanford, California, 94305, USA*
marandi@caltech.edu

Abstract: We demonstrate first-order phase transition in coupled optical parametric oscillators corresponding to an abrupt transition from degenerate to non-degenerate oscillation at a critical cavity detuning which can be utilized for enhanced sensing, and information processing.

Driven dissipative systems in non-equilibrium steady states exhibit a wide range of intriguing phenomena including self-organization, pattern formation, emergent phase and dynamical phase transition [1]. Networks of such driven-dissipative systems feature complex dynamics that leads to enriched behavior from the ensuing interplay of the degrees of freedom of the individual constituents. Driven nonlinear optical resonators provide a fertile ground to explore non-equilibrium physics [2, 3]. Here, we show that a system of coupled optical parametric oscillators (OPOs) near degeneracy can undergo an abrupt dynamical first-order phase transition from its degenerate (ordered state) to non-degenerate (disordered) state by cavity detuning (control parameter). While, second-order spectral phase transition can be observed in a single optical parametric oscillator [2], the first-order phase transition that we explore here is unique to the interacting dynamics in a system of coupled optical parametric oscillators.

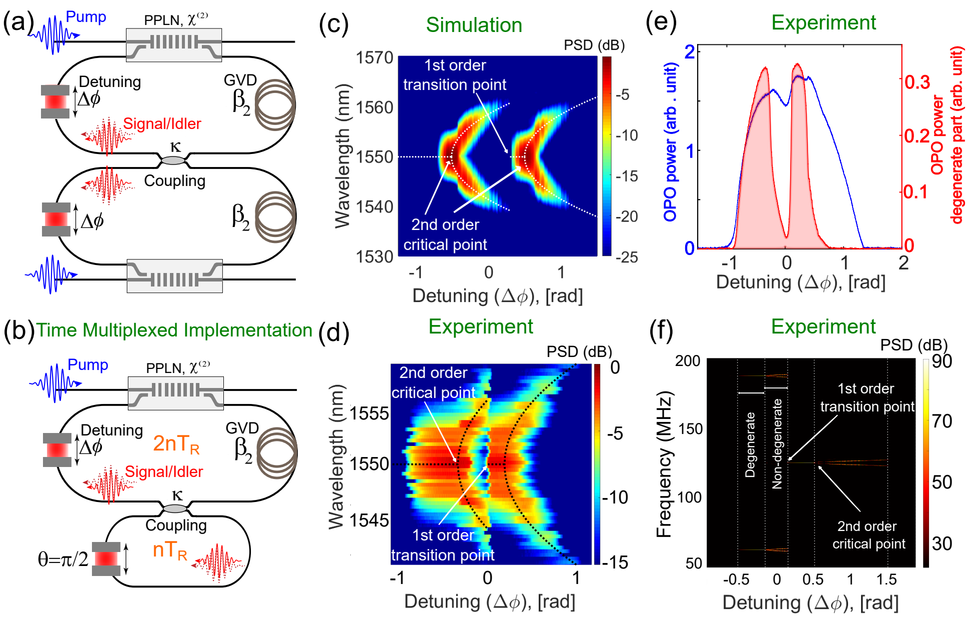

Fig. 1. a) Conceptual schematic of the coupled OPOs comprising of two identical doubly-resonant OPOs. b) Schematic of the time-multiplexed coupled OPOs used in the experiments. Optical spectrum as a function of cavity detuning obtained through c) numerical simulation and d) experiments. e) OPO output power plotted as a function of cavity detuning alongside the power contained in the degenerate portion, which shows the existence of two distinct degenerate regimes separated by a non-degenerate regime. f) Radio-frequency beat-note captured in the homodyne measurement which highlights the abrupt discontinuity at the first-order transition point.

We consider coupled doubly-resonant OPOs [4], where the signal and the idler are resonant in a fiber feedback cavity [5] as shown in Fig. 1(a). We realize the coupled system in a time-multiplexed architecture as shown in Fig. 1(b) [6]. The parametric gain is provided by the quadratic nonlinearity of a periodically poled lithium niobate waveguide [2,5]. The synchronously pumped OPO represents a multimode (longitudinal modes) system, and the distribution of these modes is controlled by the cavity dispersion realized using a suitable combination of polarization-maintaining and dispersion-compensating fibers. The dispersive coupling is introduced using the auxiliary cavity (without the PPLN), which is half the length of the main OPO cavity. The cavity lengths are prepared such that the repetition rate of the mode-locked pulsed pump is close to being an integer multiple of the cavity free spectral range. The cavity detuning, being the control parameter, is varied using piezoelectric transducers on delay stages.

In the CW-driven, high-finesse limit, the coupled OPOs are governed by the following mean-field evolution equations:

$$\frac{\partial a}{\partial \xi} = (-\alpha + \mathrm{i}\Delta\phi)a + ga^* - \mathrm{i}\frac{\beta_2}{2}\frac{\partial^2 a}{\partial t^2} + \mathrm{i}\kappa b - \left[\frac{\varepsilon^2}{2u^2}\int_0^{Lu}(Lu-\tau)a(t-\tau)^2 d\tau\right]a^*, \tag{1a}$$

$$\frac{\partial b}{\partial \xi} = (-\alpha + \mathrm{i}\Delta\phi)b + gab^* - \mathrm{i}\frac{\beta_2}{2}\frac{\partial^2 b}{\partial t^2} + \mathrm{i}\kappa a - \left[\frac{\varepsilon^2}{2u^2}\int_0^{Lu}(Lu-\tau)b(t-\tau)^2 d\tau\right]b^*, \tag{1b}$$

where, a,b describes the signal envelope under the slowly varying envelope approximation limit for OPO_1 and OPO_2 respectively. Here ξ, t refers to the slow time and the fast time, respectively. α, $\Delta\phi$, β_2, and g denote the loss, detuning, second-order group velocity dispersion (GVD), and the phase-sensitive parametric gain, respectively. g in the CW-limit is expressed as εbL, where b is the pump amplitude. L refers to the cavity round-trip length where the nonlinear interaction is encountered, ε includes the strength of the nonlinear interaction and u is the walk-off parameter. The last term to the right of the equation is responsible for the gain saturation. κ is the strength of the dispersive coupling. The coupling results in the formation of supermodes (symmetric and anti-symmetric) around the cavity detuning ($\Delta\phi = \kappa$ and $\Delta\phi = -\kappa$). Each of these terms are normalized by suitable normalization factors. Small-signal stability analysis of these system of equations reveals the most unstable signal/idler spectral positions. The coupled OPOs above threshold will follow the spectral distribution dictated by the maximum gain principle and will resemble the likes of Fig. 1(c,d). The competition between the two second-order spectral phase transitions centered around the symmetric and anti-symmetric mode results in the first-order phase transition which leads to an abrupt discontinuity when the coupled OPOs transit from degeneracy to non-degeneracy. The second-order spectral phase transitions are characterized by the presence of a critical point and are accompanied by square-root splitting in the non-degenerate regime [2].

Figure 1(e) shows the coupled OPOs output power as a function of detuning. The power contained only in the degenerate regime is also plotted alongside, which is captured by placing a bandpass filter (centered at the half-harmonic with FWHM of 1 nm) preceding the photo-detector. The appearance of two distinct degenerate peaks suggests the existence of the non-degenerate phase in between. The radio-frequency beat-note spectrum is shown in Fig. 1(f). The degenerate regime possesses a single beat-note while the non-degenerate regime exhibits multiple beat-notes corresponding to the beating of the signal and idler frequency comb with the local oscillator frequency comb. The abrupt discontinuity at the first-order transition point is also revealed.

We have shown that coupled OPOs at the first-order transition point can undergo an abrupt spectral discontinuity. Our results shed light on spectral behaviors of a system of coupled nonlinear photonic resonators which can potentially enable new opportunities for sensing and information processing. The discontinuous behavior around the transition point can be a resource for enhanced sensing [7], and the dynamics around the critical point may be beneficial for information processing based on optical Ising machines [6].

This work is supported by AFOSR award FA9550-20-1-0040, ARO grant no. W911NF-18-1-0285, NSF Grant No. 1846273 and 1918549, and NASA.

References

1. M.C. Cross, and P.C. Hohenberg, Reviews of modern physics **65 (3)** , (1993).
2. A. Roy, S. Jahani, C. Langrock, M. Fejer, A. Marandi, Nat. Comm. **12(1)** (2021).
3. A. Tkan, J. Riemensberger, K. Komagata, S. Hönl, M. Churaev, C. Skehan, H. Guo, R.N. Wang, J. Liu, P. Seidler, T. Kippenberg, Nat. Physics **17(5)** , (2021).
4. R. Hamerly, A. Marandi, M. Jankowski, M. Fejer, Y. Yamamoto and H. Mabuchi, PRA **94(6)** , (2016).
5. C. Langrock, and M.M. Fejer, Optics letters **32(15)** , (2007).
6. A. Marandi, Z. Wang, K. Takata, R.L. Byer, and Y. Yamamoto, **8(12)**, (2014).
7. H. Hodaei, A. U. Hassan, S. Wittek, H. Garcia-Gracia, R. El-Ganainy, D. N. Christodoulides, and M. Khajavikhan, Nature 548 (7666) , (2017).