

4-Field spontaneous symmetry breakings in photonic molecules

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Abstract. We present in this work a study of 4-field symmetry breakings in two photonic molecule structures consisting of two identical microresonators with distinct coupling arrangements. Mediated by the Kerr-interaction, the systems also display different 2-field symmetry breakings, periodic switching and chaos. The wide range of nonlinear optical dynamics makes the system ideal for all-optical switching, optical memories, telecommunication systems, polarization controllers and integrated photonic sensors.

1 Introduction

Like other domains of physics [1-2], Spontaneous symmetry breakings (SSB) of light fields circulating in microresonators have been an intriguing subject in the domain of optical nonlinearities. SSBs in Kerr-resonators have been observed between counter propagating fields [3-6] and two orthogonal polarization components [7] of light. Recently, the possibility of 4-field SSB in microresonators has been predicted [8]. In this work, we show that 4-field SSBs are also viable in two different arrangements of photonic molecules formed by two identical microresonators having different inter-resonator coupling mechanisms.

2 Systems under consideration

Photonic molecule refers to systems with two identical microresonators. In this study, we theoretically investigate the occurrence of SSB in two different photonic molecule structures [9] as depicted in Fig. 1. In the first system, which we call system “o|o” (Fig. 1a), the fields within each resonator is coupled to each other through the coupling waveguide symmetrically placed in between them. Whereas, in the second system, dubbed as “|oo|” system (Fig. 1b), light-fields from one resonator scatter directly to the other resonator causing a geometrical overlap of the field components.

The systems are modelled by the following equations,

$$\begin{aligned} \dot{a}_{1\pm,2\pm} = & \left(i\Delta - \frac{\kappa}{2}\right) a_{1\pm,2\pm} + \zeta a_{2\pm,1\pm} + \\ & iU|a_{1\pm,2\pm}|^2 a_{1\pm,2\pm} + i2U|a_{1\mp,2\mp}|^2 a_{1\pm,2\pm} + \sqrt{\kappa_e} S_{in}, \end{aligned} \quad (1)$$

where $|a_{j\pm}|^2$ is the circulating average photon number in j^{th} resonator with $\pm$ symbol representing the two

mutually orthogonal circular polarizations, Δ is the cavity detuning, and total loss $\kappa = \kappa_l$ (internal losses) + κ_e (external losses). The inter-resonator coupling is described by the term ζ . For system “o|o”, $\zeta = -\kappa_e/2$ [10], and for system “|oo|”, $\zeta = iJ$, where J is the coupling rate between the two resonators [11]. The Kerr coefficient U appears in the fourth and fifth terms in the right-hand side of Eq. (1), which describe the self- and the cross-phase modulations respectively. The input photon flux to the system is given by $|S_{in}|^2$.

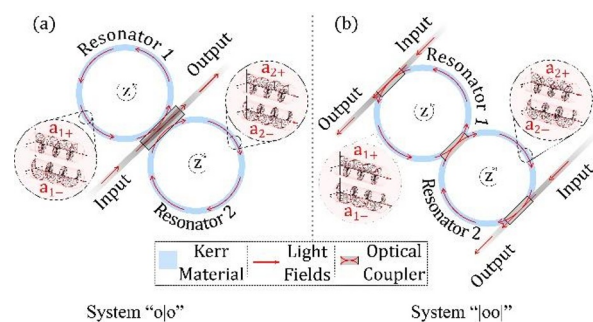


Fig. 1. Schematics of the two photonic molecule systems studied in the work.

3 Results and Discussions

Both the systems studied in this work display a rich collection of SSB phenomena. In system “o|o”, we observe two different types of 2-field SSB, whereas in system “|oo|”, three different types of 2-field SSB are observed. In both systems, 4-field SSB is observed, along with periodic switching [6] and chaos. The steady states of the systems are studied in two different ways, for analytical modelling, we set $\dot{a}_{1\pm,2\pm} = 0$, which is very much helpful to analyse 2-field SSBs. However, for 4-field asymmetries, solving the set of 4-coupled equations is quite difficult. Therefore, we also simulate Eq. (1) for

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various input parameters over sufficient amount of time and record the final values of the circulating photon numbers. The input photon flux scans for both systems are depicted in Fig. 2 and the different switching phenomena are presented in Fig. 3.

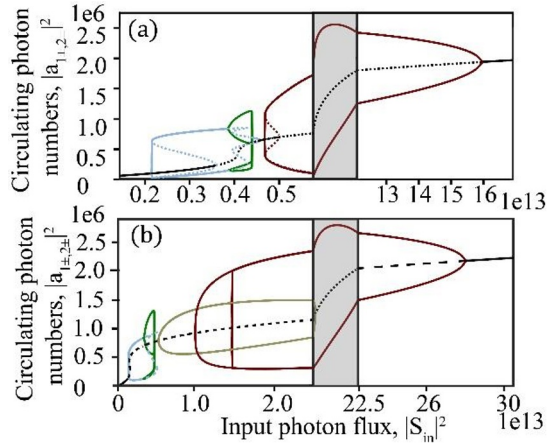


Fig. 2. Input photon flux scans of system “o|o” (a) and “||oo” (b). In both cases, for small photon fluxes, circulating field components calculated in terms of the photon numbers behave symmetrically. After a threshold of input photon flux, the two field components in each resonator pair up and one of the pairs is enhanced while the other is suppressed (blue lines). Further increasing input power, we observe full asymmetry where all the field components behave asymmetrically (green lines). After the closure of the 4-field SSB bubble, in both systems, another 2-field SSB region is observed where one field with certain polarization in a resonator pairs up with the orthogonal polarization component of the other resonator (brown lines). In system “||oo”, apart from this, another SSB bubble is observed, where fields with same polarizations in both resonators pair up (yellow lines).

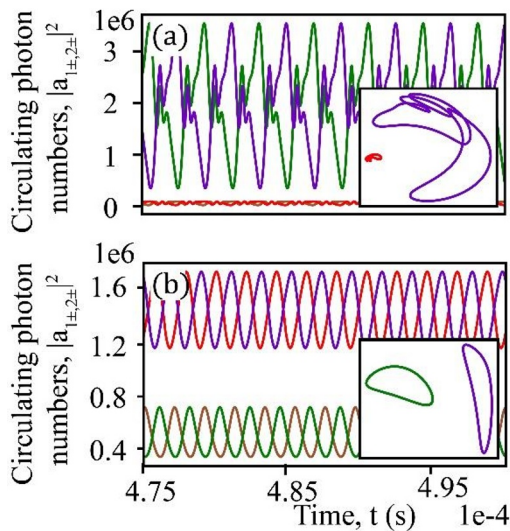


Fig. 3. Different types of field switching oscillations in time in system “o|o” (a) and “||oo” (b) respectively. Different pairings of the switching fields are observed in both the systems. Sinusoidal periodic switching is only observed in system “||oo”. Inset showing the phase space of the fields.

With extended regions of 4-field asymmetry these two systems will help in the realization of four way all optical switches, and improve the current resonator-based polarization controllers [7]. This work will further likely add to the systems where vector solitons [12] can be observed.

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