Reversing the transition from an unbroken to a broken phase in a PT-symmetric dimer laser

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Abstract: We experimentally demonstrate that in the presence of gain and loss, the order in which the PT-symmetry breaking occurs can be reversed in a semiconductor coupled micro-cavity laser system as a result of nonlinear interactions.

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The notion of parity-time (PT) symmetry emerged within the context of open quantum systems where it was found that a wide class of non-Hermitian Hamiltonians can still possess entirely real eigenvalue spectra as long as they commute with the anti-linear PT operator [1]. Configurations described by such Hamiltonians are known to support two distinct phases associated with unbroken and broken PT-symmetry where the transition between these two regimes is marked by the presence of an exceptional point [2]. As recently indicated in several studies, optics can provide a fertile ground where such concepts can be realized and experimentally observed. What facilitates this possibility is the formal equivalence between the quantum Schrödinger and the optical wave equation, where the gain-loss parameters are responsible for introducing non-Hermiticity. Along these lines, a number of counterintuitive effects have been observed in photonic PT-arrangements that have no counterpart whatsoever in Hermitian settings [2, 3]. It is commonly believed that in such prototypical optical realizations, upon an increase in the gain-loss contrast, a system will always move from an unbroken to a broken-symmetry phase [1-3]. At this point, the question arises as to whether this transition can also occur in reverse order-especially in light of the fact that these common notions stem from linear theories.

On the contrary, it was recently suggested that in periodic PT lattices the eigenvalue spectrum can be restored to the real domain through the presence of conservative nonlinearities [4]. In this work we experimentally demonstrate for the first time such a reversed transition. This is accomplished in a coupled pair of semiconductor micro-ring PT-symmetric InP lasers-similar to that employed in Ref. [5]. As we will see, what is responsible for this behavior is the underlying nonlinear saturation in both the gain and loss processes in the two cavities. A schematic of this configuration is shown in Fig. 1 (a). In our experiments we found that the steady-state intensity (I_1) in the micro-ring with gain, is always higher than that in the lossy counterpart (I_2), when the gain level is below a certain critical value. This is of course characteristic of a broken (B) PT-phase. On the other hand, once the gain-loss contrast exceeds this threshold, the solutions assume an unbroken PT-symmetric form (U), having equal intensities in both micro-ring cavities of the dimer. This behavior is depicted in Fig. 1(b).

Fig. 1. (a) A PT-symmetric coupled arrangement of two micro-rings where one of them is optically pumped. (b) An SEM image of the micro-ring lasers used. (c) Steady-state field intensities in the ring with gain (I_1) and ring with loss (I_2) are shown as a function of the gain parameter, g. The loss values are chosen to be $\gamma = 0.1$ and $f = 2$. B-represents broken (purple) and U-unbroken symmetry (yellow). Before the critical value of $g_c = 2.4$ is crossed, the solutions are in the broken-PT phase with unequal intensities and afterwards, light is equally distributed in an unbroken PT-symmetric fashion.

Analytical results for the B → U transition point and the steady-state intensities in the unbroken phase were derived considering the following (dimensionless) temporal differential equations describing the structures in Fig. 1(a) and (b),

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$$\dot{\psi}_1 = -\gamma\psi_1 + \left(\frac{g}{1+|\psi_1|^2}\right)\psi_1 + i\psi_2 \quad (1)$$

$$\dot{\psi}_2 = -\gamma\psi_2 - \left(\frac{f}{1+|\psi_2|^2}\right)\psi_2 + i\psi_1. \quad (2)$$

Here, ψ_1 and ψ_2 represent the modal field amplitudes in the cavities with gain and loss respectively and $\dot{\psi} = d\psi/dt$ etc. Note that a PT-configuration is established here by simply subjecting one micro-ring to optical pumping while keeping the other un-pumped. Scattering losses are denoted by γ, and g and f respectively represent the unsaturated values of gain and loss due to the quantum wells in the semiconductor device. The parameter values are normalized with respect to the coupling that is on the order of $\sim 10^{11}\mathrm{s}^{-1}$. Lasing thresholds were obtained through linearization, revealing that lasing actually starts in the broken PT phase if $(\gamma + f) > 1$, which is the case in our experiments. This is due to the fact that the large amount of loss, in a way, decouples the two cavities and the light mostly tends to reside in the ring with gain (broken symmetry) therefore possessing a lower lasing threshold when compared with the overall loss in the system. Interestingly, initial parameter conditions in the linear phases also have a significant impact on the ensuing nonlinear dynamics.

In this region, i.e. $(\gamma + f) > 1$, the system first moves directly into the nonlinear broken regime where a single longitudinal mode exists in the emission spectrum. If the pumping level is increased under these circumstances, the eigenmodes of the system remarkably transition into a set of unbroken PT-symmetric states exhibiting two real eigenvalues that correspond to a pair of longitudinal lasing modes. Conversely however, if the system starts lasing in an unbroken PT-phase, i.e. when $(\gamma + f) < 1$, then it remains there in spite of the nonlinearity. Note that solutions in both these regimes are found through a steady-state eigenmode analysis. The nonlinear modes in the symmetric phase are given by, $\sqrt{(g-f)/(2\gamma) - 1}\,(1, \pm e^{\pm i\theta})$, where $\sin\theta = \gamma(g+f)/(g-f)$, and the nonlinear phase transition shown in Fig. 1(c) occurs at $g_c = f(1+\gamma)/(1-\gamma)$. Interesting to note is the formal equivalence of these modes with the linear PT-symmetric eigenvectors. Another relevant aspect is the behavior of the eigenvalues that exhibit a characteristic square-root bifurcation, as shown in Fig. 2(a), when entering the nonlinear unbroken regime.

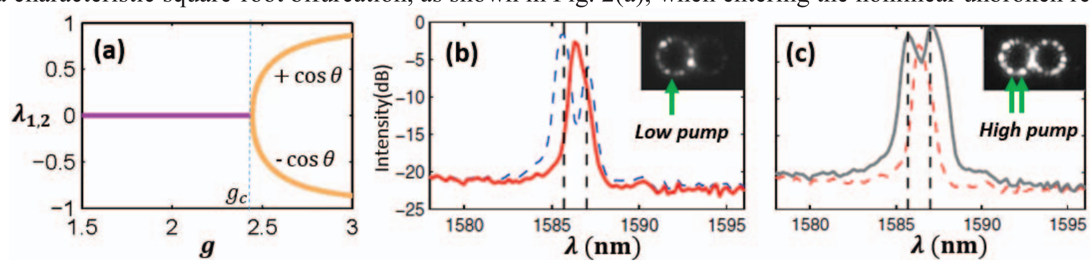

Fig. 2. (a) Square root PT-bifurcation at a nonlinear phase transition point. (b) Experimental observation of the broken PT-phase at a pump power of 0.4 mW. Upon doubling of the pump power, the steady state acquires a PT-symmetric form, as in (c) with equivalent intensities

An experimental verification of this effect was carried out on a set of coupled micro-rings having an outer radius of 10 µm, a width of 500 nm and comprising six InGaAsP quantum wells. The separation between the micro-rings was 50 nm which ensures that detuning has negligible effects on the field dynamics due to a strong coupling. When the pump power is small (but still above threshold) lasing is shown to occur in the broken phase – red curve in Fig. 2(b) where for comparison, the dashed line in the backdrop shows the spectrum when both rings are subjected to the pump and two lasing lines exist due to the coupling induced degeneracy splitting. A single line appears upon blocking the pump beam from one ring. When the pump power over the exposed micro-ring is doubled, the system goes into the unbroken PT-symmetric phase with both rings lit-up, as depicted in Fig. 2(c). Here the two lines correspond to the two real eigenvalues $\lambda_{1,2}$. This observation confirms the prediction that nonlinear saturation effects can indeed reverse the order in which symmetry breaking occurs.

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