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Creation of stable dark and anti-dark solitons in polariton dyad

YAN XUE,[1,*] YAN JIANG,[1] GANG WANG,[1] RONG WANG,[1] SHOUHUA FENG,[2] AND MICHAŁ MATUSZEWSKI,[3]

[1]*College of Physics, Jilin University, Changchun 130012, China*
[2]*State Key Lab of Inorganic Synthesis and Preparative Chemistry, College of Chemistry, Jilin University, Changchun 130012, China*
[3]*Instytut Fizyki Polskiej Akademii Nauk, Aleja Lotników 32/46, 02-668 Warsaw, Poland*
[*]*xy4610@jlu.edu.cn*

Abstract: By designing an appropriate defect potential in a nonresonantly pumped exciton-polariton condensate, the polariton dyad consisting of two spatially separated condensates with phase locking can be realized. We use the phase coupling of the polariton dyad to investigate the existence of both dark and anti-dark solitons in the condensates. Surprisingly, these dissipative solitons appear to be stable and are not affected by the noise both from the initial condition and from the propagation. We show that these stable solitons are transformed from a spontaneously created metastable states by choosing the state with the highest particle number.

OCIS codes: (240.5420) Polaritons; (190.5940) Self-action effects; (190.6135) Spatial solitons.

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1. Introduction

Strong coupling of semiconductor excitons to microcavity photons results in a family of bosonic optoelectronic excitations, called polaritons [1, 2]. The discovery of these mixed quasi-particles opened a path for the development of a new research field allowing for the direct investigation of novel aspects of light-matter interaction. The extremely small effective mass of a polariton, few orders of magnitude smaller than that of the electron, makes it possible to observe Bose-Einstein condensation at a few Kelvin or even at room temperature [3–6]. At the same time, the strong exciton-mediated interparticle interactions renders polariton condensates as a promising test bed for many-body quantum technologies [7, 8].

In recent years, there has been a strong interest in the nonlinear self-localized states of polariton superfluids, such as oblique dark solitons and vortices [9–11], bright spatial and temporal solitons [12–14]. In a polariton system, due to the significant losses these states are inherently dissipative, and qualitatively different from the ones existing in Hamiltonian systems. In general, they may exhibit nontrivial internal density currents, evolving in a complicated, sometimes even chaotic, manner. To date, in the coherently pumped exciton-polariton systems, both dark [9] and bright [12, 13, 15] solitons were reported to be observed, with the limited momentum and lifetime around tens of picoseconds. Recently, dark solitons were created in a high-velocity polariton waveguide, revealing a very strong nonlinearity in the conitnuous wave regime [16]. Under nonresonant pumping, only dark solitons [17, 18] have been predicted to exist for a period of time, after which they decay.

The well-established technologies of semiconductor microcavity fabrication and structuring allow for the creation of nearly arbitrary effective potentials for polaritons. In this paper, with the use of an appropriate defect potential and homogeneous pumping, we demonstrate the existence of stable dark/anti-dark solitons in spatially separated exciton-polariton condensates with phase locking, which is named a polariton dyad. The solitons are not spontaneously created during the condensate formation, but after a sudden phase transition from a pair of unstable dark solitons. Although a method [19] has been proposed to stabilize the dark soliton by use of both coherent pulse and nonresonant periodic pump fields, we note that our solution is qualitatively different from the solitons found in previous works [9, 11–14, 19, 20]: the key ingredient is the phase coupling of the polariton dyad, and the phase configuration tends to pick the state with the highest number of particles. Within this scheme, the dissipative solitons [21] in nonequilibrium polariton condensate appear to be similar to the ones present in Hamiltonian systems: they may be stable.

2. Model

In the analysis below, we consider an exciton-polariton condensate in a nonresonantly pumped one-dimensional (1D) setup, e.g. trapped in a microwire [22]. The realistic model for the system, the open-dissipative Gross-Pitaevskii equation (ODGPE), includes coupling of the condensate wave function $\psi(x,t)$ to the polariton reservoir density $n_{\mathrm{R}}(x,t)$ described by the phenomenological rate equation [23, 24]

$$d\psi = [\frac{\hbar}{2m^*}\frac{\partial^2\psi}{\partial x^2}(i + D_0 n_{\mathrm{R}}) + \frac{1}{2}\underbrace{\left(R^{1\mathrm{D}}n_{\mathrm{R}} - \gamma_{\mathrm{C}}\right)}_{R'}\psi - \frac{i}{\hbar}(g_{\mathrm{C}}^{1\mathrm{D}}|\psi|^2 + g_{\mathrm{R}}^{1\mathrm{D}}n_{\mathrm{R}} + V(x))\psi]dt + dW$$

$$\frac{\partial n_{\mathrm{R}}}{\partial t} = D_1\frac{\partial^2 n_{\mathrm{R}}}{\partial x^2} + P(x) - (\gamma_{\mathrm{R}} + R^{1\mathrm{D}}|\psi|^2)n_{\mathrm{R}} \tag{1}$$

where we assume a Gaussian perpendicular profile of $|\psi|^2$ and n_{R} of width d determined by the microwire thickness. The real coefficients D_0 and D_1 represent respectively the energy relaxation in the condensate and the spatial diffusion rate of reservoir polaritons. The rate of stimulated scattering of polaritons from the reservoir $R^{1\mathrm{D}}$ and the interaction coefficients $g_i^{1\mathrm{D}}(i = C, R)$ between condensate and reservoir polaritons are rescaled in the one-dimensional case by $\frac{1}{\sqrt{2\pi d^2}}$. $P(x)$ and γ_{R} are the creation and relaxation rates of the polariton reservoir, γ_{C} is the polariton loss rate, m^* is the effective mass of lower polaritons and $V(x)$ is the external potential. While the classical fluctuations are taken into account in the initial polariton field, it is possible to include the effect of quantum fluctuations on the level of classical fields approximation [24–26] with the addition of a complex stochastic term in the truncated Wigner approximation (TWA)

$$< dW(x)dW(x') >= 0, \quad < dW(x)dW^*(x') >= \frac{dt}{2dx}(R^{1D}n_{\mathrm{R}} + \gamma_{\mathrm{C}})\delta_{x,x'} \tag{2}$$

In a nonequilibrium driven system without noise, above the condensation threshold $P(x) > P_{\mathrm{th}} = \gamma_{\mathrm{C}}\gamma_{\mathrm{R}}/R^{1\mathrm{D}}$, we investigate the large distance behavior of a single pumped condensate (by assuming $P(x) = P_0$ and $V(x) = V_0$). We consider the steady state solution for Eq. (1) with the Madelung transformation: $n_{\mathrm{R}}(x,t) = \frac{P_0}{\gamma_{\mathrm{R}} + R^{1\mathrm{D}}\rho(x)}$ and $\psi(x,t) = \sqrt{\rho(x)}e^{i(S(x) - \mu t/\hbar)}$ with the number density $\rho(x) = \frac{P_0 - P_{\mathrm{th}}}{\gamma_{\mathrm{C}}}$ determined by a balance of gain and loss, phase $S(x)$ and chemical potential μ for this condensate. Neglecting the spatial derivatives of the number density by assuming a sufficiently large pumping spot, the imaginary part of Eq. (1) leads to integrated form of the Bernoulli equation:

$$\mu = \frac{\hbar^2}{2m^*}\left(\frac{d}{dx}S(x)\right)^2 + g_C^{1D}\rho(x) + g_R^{1D}n_R + V_0 \simeq \frac{\hbar^2}{2m^*}\left(\frac{d}{dx}S(x)\right)^2 + \frac{g_C^{1D}P_0}{\gamma_C} + \frac{g_R^{1D}\gamma_C - g_C^{1D}\gamma_R}{R^{1D}} + V_0 \tag{3}$$

It follows that far away from the pumping spot the steady state wave function of the single condensate can be approximated as $\psi(x) = \sqrt{\rho(x)}e^{ik_c x}$ with the outflow wave number $k_c \simeq \frac{\sqrt{2(\mu-V_0)m^*}}{\hbar}$. Here $g_R^{1D}\gamma_C = g_C^{1D}\gamma_R$ is set to be considered.

The wave function of two condensates with the same size and separated by the distance a can be approximated as the sum of the individual ones:

$$\tilde{\psi}(x) = \psi(x + \frac{a}{2}) + e^{i\theta}\psi(x - \frac{a}{2}) \tag{4}$$

where θ is the phase difference between the two condensates. The total number of particles in the condensates can then be written as

$$I = \int |\tilde{\psi}(x)|^2 dx \approx 2\int \rho(x)dx + k_c|\psi(k_c)|^2 J_0(k_c a)\cos(\theta)/\pi \tag{5}$$

where $\psi(k_c) = 2\pi\int_0^\infty \rho(x)\exp[ik_c x]J_0(k_c x)x dx$ and J_0 is the Bessel function. To maximize the total occupation number for the condensate, the phase coupling of two condensates ($cos(\theta)$) is presented to depend both on the separation distance a and outflow velocity from condensate (or outflow wave number k_c). One obtains in-phase coupling with $J_0(k_c a) > 0$ and anti-phase coupling while $J_0(k_c a) < 0$. These two condensates, phase locked either in a symmetric or antisymmetric state, are named as polariton dyad [27].

3. Dark and anti-dark solitons

In the presence of an external potential $V(x)$, a much richer dynamics appears. In the case where $V(x)$ is a random potential, which naturally results from the fluctuation during the microcavity growth, its presence induces spatial inhomogeneities of the condensate phase [28], coherence and density modulation [29–31] which were observed and explained within a similar theoretical formalism as used here.

In this work, we examine the exciton-polariton condensate with an external potential $V(x)$ given by

$$V(x) = \begin{cases} 0 & |x| \leq a \\ V_0 & |x| > a \end{cases} \tag{6}$$

here $V_0 = 0.2$meV is the external potential strength and $a = 1\mu$m is the width that mimics the finite-size effect of the defect potential. The system of coupled equations (Eq. (1) together with Eq. (6)) are numerically solved in time using a fifth-order Adams-Bashforth-Moulton predictor-corrector method. Random low-intensity white noise [as shown in Fig. 1(a)] is seeded as an initial condition for the condensate field $\psi(x, 0)$. The noise in the initial condition, as well as the TWA noise in the evolution equation allow to investigate the stability properties through the observation of response of the system in the long-time dynamics. We note that while this method does not provide an exact answer about the stability, it is able to detect unstable modes provided that the evolution time is long enough. One should be aware, however, that more detailed methods, such as perturbation theory, could be used to confirm the stability of the solutions with a higher degree of accuracy.

We perform a systematic study in the case of homogeneous pumping, $P(x) = P_0$, with the following parameters (close to those of the experimental setup of [32]): $m^* = 5 \times 10^{-5} m_e$, $\gamma_R = 2.0 \times \gamma_C = \frac{1}{3ps}$, $g_R^{1D} = 2 \times g_C^{1D} = 0.9547 \mu$ev μm, $R^{1D} = 2.24 \times 10^{-4} \mu$m ps^{-1}, $D_0 = 4 \times 10^{-3}$ and $D_1 = 1 \times 10^{-3}$. We note that the polariton reservoir corresponds to the "active" exciton population that can directly scatter to the polariton condensate and has much shorter lifetime than the "inactive" excitons and free carriers at high energy levels. The latter are not subject to a considerable back-action from polaritons and not relevant for the stability properties of the system.

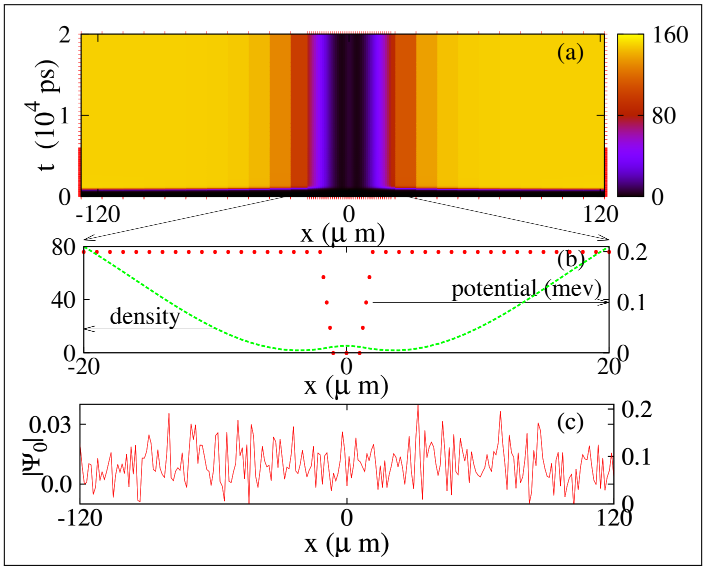

Fig. 1. (a) Temporal evolution of polariton density $|\psi(x,t)|^2$ towards polariton dyad in a 1D wire with defect potential, starting from a small initial noise. (b) Spatial profile of the corresponding density of Fig. 1(a) at t=10000ps (greed dashed line) and the external potential (red dotted line).(c) The initial noise

We study the temporal evolution of the condensates spatially separated by the defect potential, and firstly concentrate on the case of lower pumping power just above the condensation threshold [as shown in Fig. 1 with $P_0 = 1.1 \times P_{th}$]. With such a weak pumping power close to the threshold P_{th}, the effect from the nonlinear interaction part $g_C^{1D} n_p$ is negligible with respect to that from the kinetic and potential parts in Eq. (1). It may seem natural in this case to treat two polariton condensates as two dissipative counter-propagating linear waves with wave number k_c. They meet with each other at the center of the defect potential and the resulting interference appears sink-type constructive. It is shown by the green dashed line in Fig. 1(b). This indicates that the polariton dyad in in-phase synchronization is observed with a homogeneous continuous pumped laser, which is different as that in [27], where the phenomena of polariton dyad is demonstrated with the application of two spatially separated pulse lasers. Additionally, the green dashed line in Fig. 1(b) shows that the scale of the extension of the interference is wider than that of the defect region, which is affected by the relatively small wave number k_c. The larger of the value for the wave number k_c, the narrower of the scale for the extension of the interference.

This simple in-phase state of a polariton dyad can be dramatically modified as one increases the pumping power P_0 [as shwon in Fig. 2 with $P_0 = 1.2 \times P_{th}$]. Since the nonlinear energy of polariton-polariton interaction increases dramatically with the pumping power P_0, it becomes comparable to the kinetic energy. During the procedure of two polariton condensates formation,

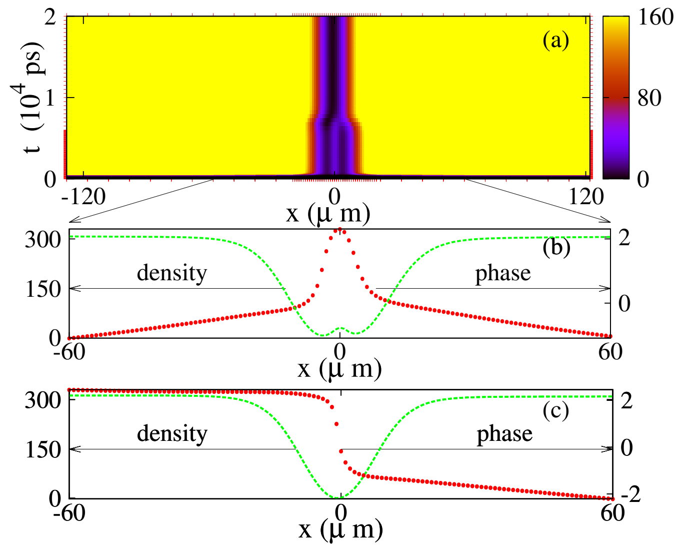

Fig. 2. (a) The dynamical evolution from the in-phase state with a pair of dark solitons to the anti-phase state with only one stable dark solion. Spatial profile of the density (green dashed line) and the corresponding phase jump (red dotted line) for the dark solitons, respectively, at t=3000ps (b) and t=10000ps (c).

the balance between the nonlinear and the kinetic parts induces the spontaneous creation of another interesting nonlinear phenomenon: a pair of dark solitons [instead of dark holes in Fig. 1] connected by a none-zero sink-type constructive interference feature, as shown in Fig. 2(a) ($t < 5\times10^3 ps$) and Fig. 2(b). Significantly, this in-phase configuration with a pair of dark solitons is not a stable but a metastable state. After a certain time of evolution, phase symmetry breaking occurs and induces the resynchronization of the polariton dyad to an anti-phase configuration, with only one dark soliton ($t > 5 \times 10^3 ps$). The corresponding density and π phase jump for the stable dark soliton state at $t = 2 \times 10^4 ps$ is shown in Fig. 2(c). The phase of the polariton dyad switches from the in-phase state to the anti-phase state.

The type of phase coupling (either in-phase or anti-phase) of the polariton dyad depends both on the width a of the defect potential and on the wave vector k_c of the out-flowing polaritons. In this work, the defect potential width of a is within the range where the two condensates are always synchronized. With a fixed distance a, both the polariton density and the wave vector k_c increase along with the pumping power P_0. If the conditions (both width a and wave vector k_c are satisfied with $J_0(k_c a) < 0$) favor formation of an anti-phase state, due to the noise present in the system a jump from one state to the other can occur, which is seen at $t \simeq 5000ps$ on Fig. 2(a), for example, but depending on the noise can occur at different times (see Appendix).Then another question comes: why this stable anti-phase configuration with only one dark soliton could not appear as an initial spontaneously created state during the procedure of polariton condensates formation? Two condensates considered in our system are nonresonantly pumped with one homogeneous field and hence have the same value of the wave number k_c. Under the influence of defect potential, the flow with the same wave number k_c occurs thanks to the repulsive polariton-polariton and reservoir-polariton interactions. In the result of interaction of two nonlinear polariton waves propagating toward the center with k_c, in-phase synchronized state is spontaneous created during the procedure of the condensates formation. It is easy to understand that the formation of the in-phase synchronized state does not rely on the value of the pumping power. However, the evolution time of the state is relevant to the pumping power: The higher of the pumping power,

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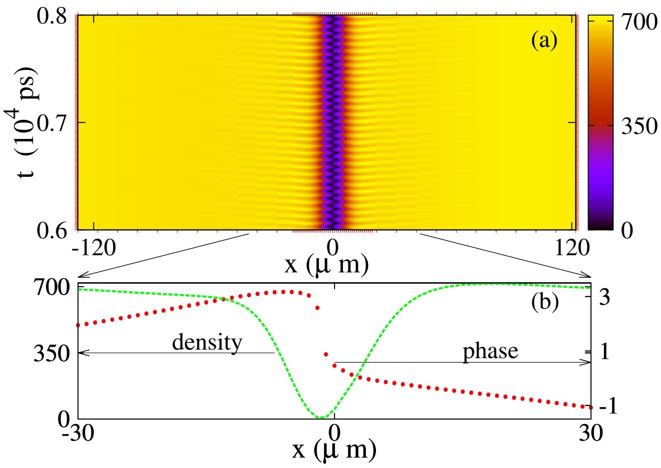

Fig. 3. (a) The oscillating dark soliton in the defect potential. Although it is a stable state, for better visual effects, we plot it only from t=6000ps to t=8000ps. (b) Corresponding density (green dashed line) and phase jump (red dotted line) at t=7000ps for the moving dark soliton.

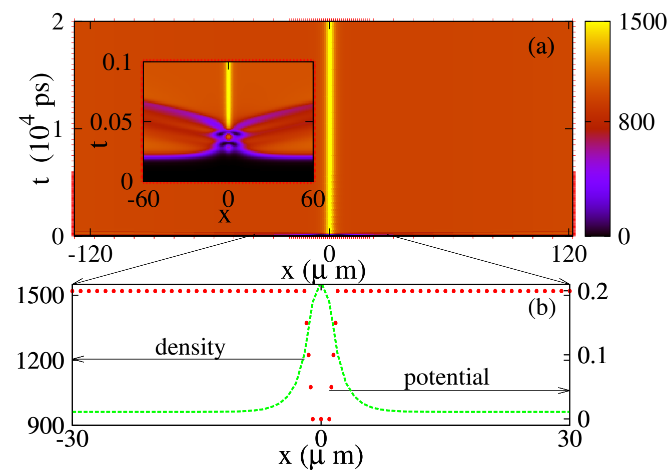

Fig. 4. (a) Observation of the anti-dark soliton (the figure and the inset have the same axis unit), (b) Spatial profile of the density (green dashed line) for the anti-dark state and the external potential $V(x)$ (red dotted line).

the shorter of the evolution time for this in-phase synchronized state. Additionally, we'd like to point out that, although the evolution time of this in-phase synchronized state is disturbed by the noise, the final observed stable anti-phase state named as dark soliton is not affected by the disorder [see Appendix].

We note that, in the regime of pumping power where balance between kinetic and nonlinear energy holds, with the increase of pumping power, the soliton varies from the stationary state ($1.1P_{th} < P_0 \leq 1.4P_{th}$) to the oscillating state ($P_0 = 1.5P_{th}$) accompanied with the phonon scattering [as shown in Fig. 3]. The width of the dark soliton is less than that of the defect potential and reduces with the increase of pumping power P_0, similar as the case discussed in [17]. Different from the creation scheme of dark soliton proposed in [17], here the dark soliton is formed due to the anti-phase coupling of two condensates but not the π phase jump as an initial seed.

With further increase of pumping power up to around $P_0 = 1.7P_{th}$, while outflow wave number k_c is modified so as to satify the condition of $J_0(k_c a) > 0$, two condensates transform into the in-phase coupling again to pick the state of the highest occupation. Fig. 4(a) shows the corresponding dynamical evolution, where the in-phase state is not sink-type as in Fig. 1 but appears anti-dark accompanied with the balance between the nonlinear and the kinetic energy. There have two in-phase synchronized states: one with a pair of oscillating dark solitons and the other with an anti-dark soliton. The former is spontaneously created as a metastable state during the procedure of condensates formation, as mentioned before. The latter is spontaneously picked as a stable state during the dynamical evolution to maximize the total occupation number for the condensate. We note that, for the in-phase state with anti-dark soliton, the healing length of the condensate $\xi = \hbar/\sqrt{2m^* g_C^{1D}|\psi|^2}$ is roughly equal to the defect potential width a.

4. Conclusion

To summarize, we demonstrated that, when two nonresonantly pumped exciton-polariton condensates are excited with a homogeneous pumping laser and a defect potential, dissipative dark and anti-dark solitons can be observed and stabilized. The formation of these solitons is related to the phase coupling of a polariton dyad and the final stable state are not affected by the random noise [see Appendix]. This opens a route to observe the stable solitons in the nonequilibrium polariotn BEC and to experimental demonstration of states which is easy to implement. Additionally it becomes an important step towards construction of low-powered opto-electronic devices.

Appendix A.

The effect of noise In the manuscript, we add white gaussian noise both at the beginning and during the propagation with a relatively small amplitude. For example, we consider 100% noise ratio in the initial seed $|\psi| = 0.01$ and 1% propagation noise ratio in eq.(2). To check the impact on the condensate state, we consider the dynamical evolution with noise of higher magnitude.

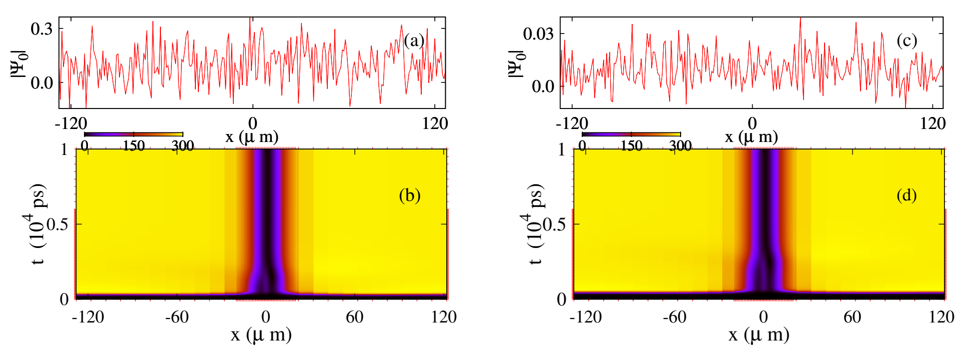

Fig. 5. The dynamical evolution from the in-phase state to the anti-phase state with different noise. (a) and (b): The initial seed is increased up to $|\psi| = 0.1$ with 100% noise ratio, the propagation quantum noise is 1%; (c) and (d): The initial seed is $|\psi| = 0.01$ with 100% noise ratio, the propagation quantum noise is added up to 10%.

or the initial classic noise, while keep the propagation quantum noise as 1% invariant, we increase the value of the initial seed up to $|\psi| = 0.1$ plus 100% noise ratio [10 times of the original one in manuscript, as shown in Fig. 5(a)]. For the propagation quantum noise as depicted in Eq. (2), we add it up to 10% but keep the initial seed the same as that in the manuscript [$|\psi| = 0.01$ plus

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100% noise ratio, as shown in Fig. 5(c)]. It is shown both in Fig. 5(b) and Fig. 5(d) that the final stable condensate state is not affected apparently by the disorder. The disorder could only affect the dynamical evolution procedure before the final state is observed. With a higher magnitude of disorder, the lifetime for the metastable state (a pair of dark solitons) is decreased.

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