

In-phase and out-of-phase interactions among Airy pulses, bright and dark solitons

X. YAN^{a,b*}, Y. LI^{a,b,*}, Z. JUN^{a,b}, G. GE^{a,b}, C. SUN^{a,b}, D. QUAN^{a,b}, M. WANG^{a,b}, X. ZHANG^{a,b}, Q. CHEN^{a,b}, Y. ZHANG^{a,b}, M. ZONG^{a,b}

^a*School of Opt-Electronic Engineering, Zaozhuang University, Zaozhuang 277160, China*

^b*Key Laboratory of Optoelectronic Information Processing and Display in Universities of Shandong, Zaozhuang University, Zaozhuang, 277160, China*

We numerically simulate dynamic evolution of in-phase and out-of-phase finite-energy Airy pulses interacted with bright and dark solitons in the optical fiber as well as analyse the effects of separation parameter on evolution properties. Numerical results show that the effects of separation parameter on in-phase and out-of-phase Airy pulses interacting with bright and dark soliton pulse are entirely different. For the cases of interacting with bright soliton pulse, the attraction of beams occurs in the in-phase Airy pulse and the repulsion in the out-of-phase one. However, for the cases interacted with dark soliton pulses, in-phase and out-of-phase Airy pulses undergo only repulsion progress. Depending on the peak intensity varying with the propagation distance, the effect of separation parameter effect has a slightly different impact on the evolution of Airy pulses interaction with bright and dark soliton pulses.

(Received December 10, 2018; accepted October 9, 2019)

Keywords: soliton pulse; separation parameter; in-phase and out-of-phase Airy pulse

1. Introduction

Airy wave packets were first predicted by Berry and Balazs [1] in quantum mechanics in 1979. However, these packets feature infinite energy, which causes their experimental generation impossible. G.A. Siviloglou et al. accomplished experimental generation of Airy wave packets in optical domains by modulating time exponential functions [2,3]. Finite-energy Airy pulse [4-11], as a self-accelerating nondiffracting optical pulse, has been employed for various potential applications, such as optical trapping and micro-manipulation [12], light bullet generation [8,13,14], curved plasma filament generation[15], supercontinuum generation[16], optical routing[17], and so on.

The dynamics of single finite-energy Airy pulses[18] and related propagation properties have been investigated [14, 19-32]. However, interactions between Airy beams with other optical pulses have not attracted much attention. Particularly, symmetric Airy beams readily display self-focusing in a nonlinear (NL) medium [33, 34], the interaction with bright and dark soliton pulses[35] with varying distance between them has not but should

have been demonstrated more deeply. Indeed, the dynamics of an Airy beam in a NL medium has already been reported [20–24]. Zhang et al. [36] investigated the interactions of two in-phase and out-of-phase Airy pulses and NL accelerating beams in Kerr and saturable NL media in one transverse dimension, indicating that the interval between two incident beams is large relative to the width of their first lobes, the generated soliton pairs just propagate individually and do not interact. In nonlocal media, Shen et al.[36] studied the spatially optical soliton shedding from Airy pulses and anomalous interactions of Airy beams, showing that nonlocality provides a long-range attractive force between Airy pulses, leading to the formation of stable bound states of both in-phase and out-of-phase breathing Airy soliton which always repel in local media. However, the propagation properties of in-phase and out-of-phase Airy beams interacting with soliton pulse have not been investigated in a NL medium till now.

Here, in this paper, we investigate dynamic propagation and properties of in-phase and out-of-phase finite-energy Airy pulses interacted with bright and dark

solitons in the optical fiber. It is concluded that the effects of separation parameter on in-phase and out-of-phase Airy pulses interacting with bright soliton pulse and dark soliton pulse are entirely different. By means of the peak intensity varying with the propagation distance, the effect of separation parameter effect has a slight impact on the evolution of Airy pulses interaction with bright and dark soliton pulses. What's more, this work enriches the investigations on the nonlinear propagation property of the Airy pulse and soliton generation.

2. Theory model

In paraxial approximation, the normalized equation for the evolution of a slowly varying envelope amplitude $A(z, t)$ of the Airy pulse satisfies the nonlinear Schrödinger equation [22]

$$i \frac{\partial A}{\partial z} - \frac{\text{sgn}(\beta_2)}{2} \frac{\partial^2 A}{\partial t^2} + \gamma |A|^2 A = 0 \quad (1)$$

where z and t are the dimensionless transverse coordinate and the propagation distance, β_2 is the second-order group velocity dispersion coefficient, respectively. sgn is the signal function, if $\text{sgn}(\beta_2) < 0$, that is in the abnormal region, Eq.(1) has a bright soliton solution, while if $\text{sgn}(\beta_2) > 0$, that is in the normal region, Eq.(1) has a dark soliton solution.

The incident pulse is composed of two shifted counter propagating Airy pulses with a relative phase between them,

$$A(0, t) = Ai(t-B)\exp[a(t-B)] + \exp(ip\pi)Ai[-(t+B)]\exp[-a(t+B)], \quad (2)$$

where Ai represents the Airy function, a is the truncated coefficient factor, B is the pulse separation parameter, and p is the parameter manipulating phase shift, including in-phase and out-of-phase Airy pulses with $p=0$ and $p=1$, respectively.

When the two pulses propagate simultaneously in the fibre, they satisfy a set of nonlinear Schrödinger

equations,

$$\begin{aligned} \frac{\partial A_1}{\partial Z} + \frac{i}{2}\beta_{21}\frac{\partial^2 A_1}{\partial T^2} &= i\gamma_1[|A_1|^2 + 2|A_2|^2]A_1 \\ \frac{\partial A_2}{\partial Z} + \frac{i}{2}\beta_{22}\frac{\partial^2 A_2}{\partial T^2} - d\frac{\partial A_2}{\partial T} &= i\gamma_2[|A_2|^2 + 2|A_1|^2]A_2 \end{aligned} \quad (3)$$

where, $Z = z/L_d$ ($L_d = t_0^2/|\beta_2|$) represents the standardized dispersion length, $T = \frac{t-Z/v_g}{t_0}$ accounts for

a standardized time coordinate, $d = v_{g1} - v_{g2}$ is the group velocity adaptation coefficient, and β_{21} and β_{22} are the GVD coefficients of A_1 and A_2 , respectively. Finally,

$\gamma_1 = n_2\omega_1/cA_{\text{eff}}$ and $\gamma_2 = n_2\omega_2/cA_{\text{eff}}$ are nonlinear coefficients that depend on A_{eff} , an effective mode area.

For our model, two types of pulse were used as the incident pulses:

$$A_1(0, T) = \text{sech}(aT), A_1'(0, T) = \tanh(T)\exp(iZ)$$

$$A_2(0, T) = Ai(T-B)\exp[a(T-B)] + \exp(ip\pi)Ai[-(T+B)]\exp[-a(T+B)] \quad (4)$$

The detail solution of the equations (3) is extremely complex and cannot be completed. Therefore, in this paper, we adopted the numerical simulation method to solve the equation. Here, we set the value of $\text{sgn}(\beta_2) = 1 \text{ ps}^2\text{m}^{-1}$ in the normal dispersion region, and the $\text{sgn}(\beta_2) = -1 \text{ ps}^2\text{m}^{-1}$ in the anomalous dispersion region, nonlinear coefficient $\gamma_1 = \gamma_2 = 0.1 \text{ kW}^{-1}$, and the truncated parameter a is set to be 0.05, respectively. In the meanwhile, to satisfy the normalized equation, the initial intensities of in-phase and out-phase Airy pulses and soliton pulses are all set to be 1 W. In this paper, we investigate the effects of pulse separation parameter on the interactions of in-phase and out-of-phase Airy pulses interacted with bright soliton and dark soliton pulses.

3. Simulation results

3.1. Interaction with bright soliton pulse

$$(A_1(0, T) = \text{sech}(aT))$$

Fig. 1 displays the temporal dynamics of finite-energy Airy pulses interacting with a bright soliton pulse for different values of pulse separation parameter B ($B = 0, \pm 1, \pm 2, \pm 3$) and phase shift parameter p ($p = 0$ for in-phase and $p = 1$ for out-of-phase) in the anomalous dispersion regime. The major difference between the two cases is the attraction of beams in the in-phase and the repulsion in the out-of-phase case. For $B = \pm 3$ and ± 2 in the in-phase case, as depicted in Figs. 1 (a-b) and 1 (f-g), two Airy pulses undergo an initial compression process and several dispersion wave pulses will be shed from the background of the in-phase Airy pulse. Particularly, for $B = 0$ and 1, shown in Figs. 1(d-e), a central quasi-soliton pulse is shed from the in-phase Airy pulse and propagates

straight along the center. The smaller the pulse separation parameter, the stronger the central quasi-soliton pulse and the weaker the dispersion wave pulses. The reason is that the main lobe of the Airy beam with $B = 0$ is located at about $T = -1$, and there is still an interval between the two main lobes in the incidence. Therefore, the attraction is the biggest when $B = 1$ and the period of the formed soliton is then the smallest. Given the out-of-phase cases ($p = 1$), the results are shown in Figure 1 (h-n), which are fixed at the same numerical parameters as the in-phase case. The soliton pairs formed from the incidence actually repel each other, and the smaller the pulse separation parameter, the stronger the repulsion. Particularly, the repulsion of the soliton pair for $B = 0$, shown in Fig. 1 (k), is the strongest. The reason is that the soliton pair shown in Fig. 1(h) is generated from the secondary lobes, while the others are generated from the main lobes.

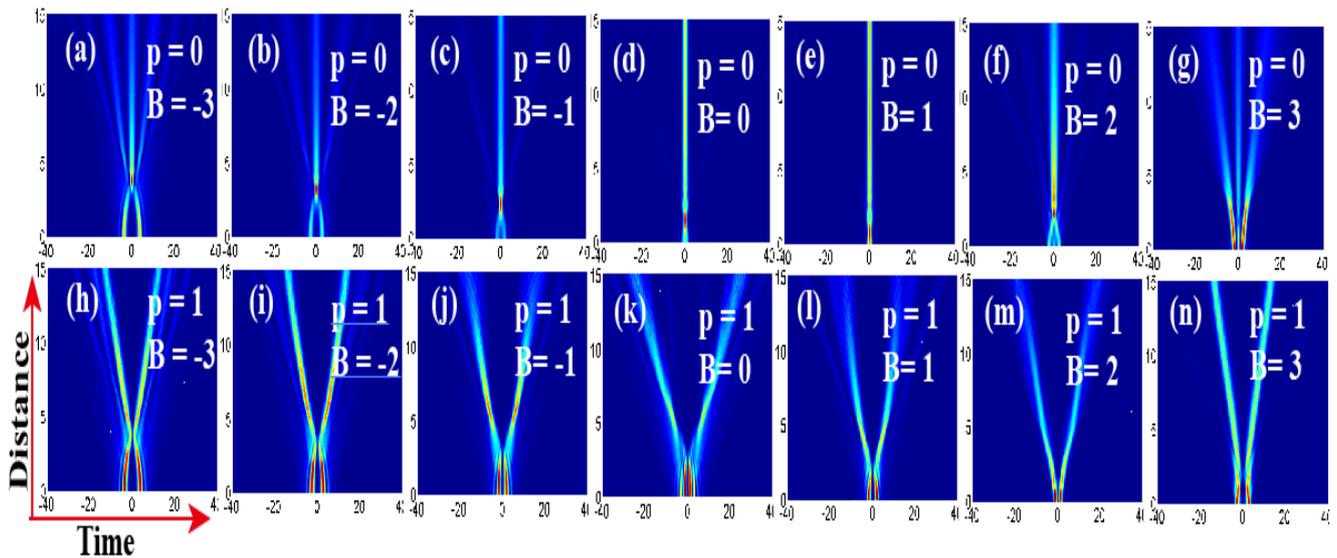


Fig. 1. Propagation dynamics of in- (a-g) and out-of-phase (h-n) Airy pulses interacting with bright soliton pulse in anomalous dispersion region for different values of pulse separation parameter B and phase shift parameter p

It is worth mentioning that, in- and out-of-phase Airy pulses interacting with a bright soliton pulse actually vary with the propagation distance in terms of their maximal normalized amplitudes, as shown in Fig. 2, where I_{max} represents the maximum of the normalized intensity. Depending on different values of B and p , the oscillation, amplitude, oscillation frequency, and the central value, are entirely different [22]. When $p = 0$, shown in Fig. 2(a),

I_{max} generally tends to be higher frequency oscillation and then maintains a steady-state value if the distance is long enough. For large separation parameter ($B = 2$ and 3), high frequency oscillation occurs in the curve of the maximum normalized intensity versus propagation distance. Particularly, for the cases of $p = 0$, in certain range of distance, for example near the first 5 propagation distances, separation parameter (B) has a significant

influence on I_{max} . Furthermore, it also can be indicated that the smaller absolute value of B , the larger the values of I_{max} during the further propagation distance. For out-of-phase cases, in that, $p = 1$, shown in Fig. 2(b), it indicates that I_{max} undergoes a higher frequency oscillation and then tends to a downward tendency and finally maintains a steady value if the distance is long enough. Differing from in-phase cases, I_{max} is smaller than that in out-of-phase cases, and it enlarges with the value of $|B|$ increases.

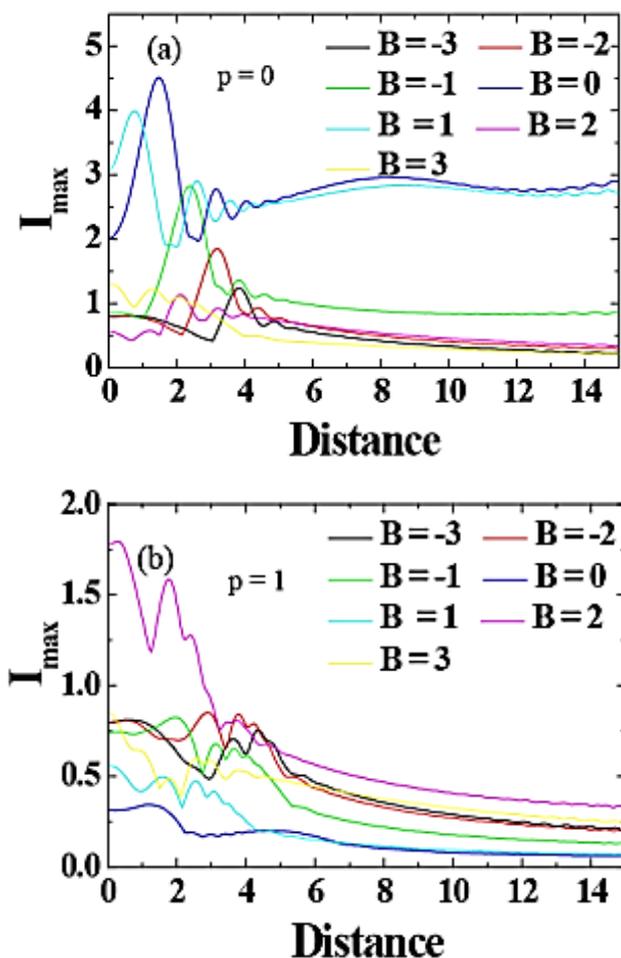


Fig. 2. The maximum of normalized intensity I_{max} of in-phase and out-of-phase Airy pulses interacted with bright soliton pulse with the normalized propagation distance for different values of separation parameter B and phase shift parameter p : (a) $p = 0$; (b) $p = 1$

3.2. Interaction with dark

$$\text{soliton}(A'_1(0, T) = \tanh(T) \exp(iZ))$$

Fig. 3 displays the temporal dynamics of finite-energy Airy pulses interaction with dark soliton pulse for different values of pulse separation parameter B ($B = 0, \pm 1, \pm 2, \pm 3$) and phase shift parameter p ($p = 0$ for in-phase and $p = 1$ for out-of-phase) in the normal dispersion regime. Different from the cases in interaction with bright soliton pulses, Airy pulses interaction with dark soliton pulses exhibit entirely different features, indicating that repulsion progress occurs in both in-phase ($p = 0$) and out-of-phase ($p = 1$) Airy pulses after undergoing an initial compression progress. For $B = \pm 3$ and ± 2 in the in-phase cases, as depicted in Figs. 3 (a-b) and 3(f-g), two Airy pulses undergoes two initial compression progresses and several dispersion wave pulses will shed from the background of in-phase Airy pulse. Particularly, for $B = 0$ and 1, shown in Figs. 3 (d-e), different from the occasions of interaction with bright soliton pulse, the Airy pulses only undergo an initial compression progress. Notably, the distance at separation parameter $B = 1$ is the smallest, indicating that the main lobe of the Airy beam with $B = 0$ is located at about -1 , and there is still an interval between the two main lobes in the incident. Furthermore, for the out-of-phase cases ($p = 1$), the results are shown in Fig. 3 (h-n), which are fixed at the same numerical parameters as the in-phase case. Similar to the occasions in in-phase cases, the soliton pairs formed from the initial out-of-phase Airy pulse and actually repel each other, and the smaller the pulse separation parameter, the stronger the repulsion. Particularly, the repulsion of the soliton pair for $B = 0$, shown in Fig. 3(k), is the strongest. The reason is that the soliton pair shown in Fig. 3(h) is generated from the secondary lobes, while the others are generated from the main lobes. It is concluded that, two quasi-soliton pulses can be obtained from out-of-phase Airy pulses if the separation parameter is certain due to that strong self-focusing and attractive force.

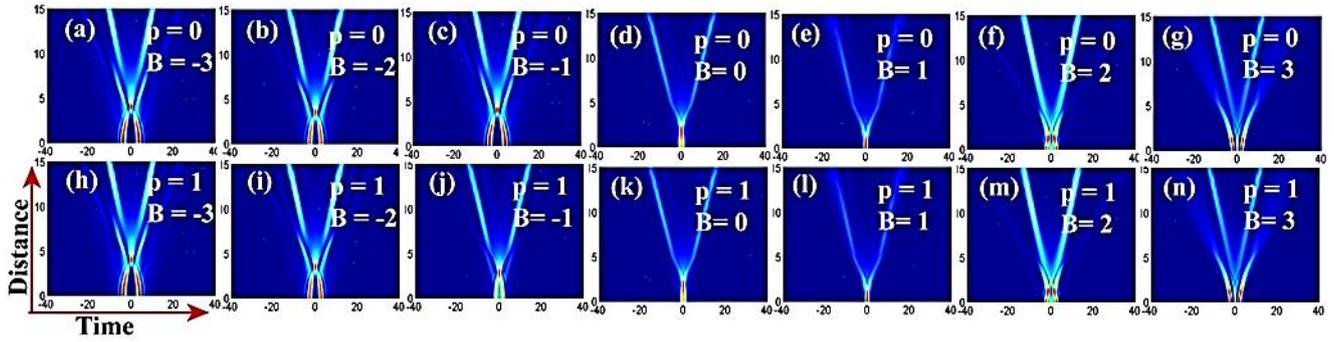


Fig. 3. Propagation dynamics of in-phase (a-g) and out-of-phase (h-n) Airy pulses interacted with dark soliton pulse in normal dispersion region for different values of separation parameter B

Fig. 4 shows the maximum of normalized intensity I_{max} of in-phase (a) out-of-phase (b) Airy pulses interaction with dark soliton for different values of separation parameter B . Similarly, for out-of-phase Airy pulse, the maximum normalized intensity I_{max} for different values of separation parameter B has a relationship of propagation distance at a certain phase parameter p .

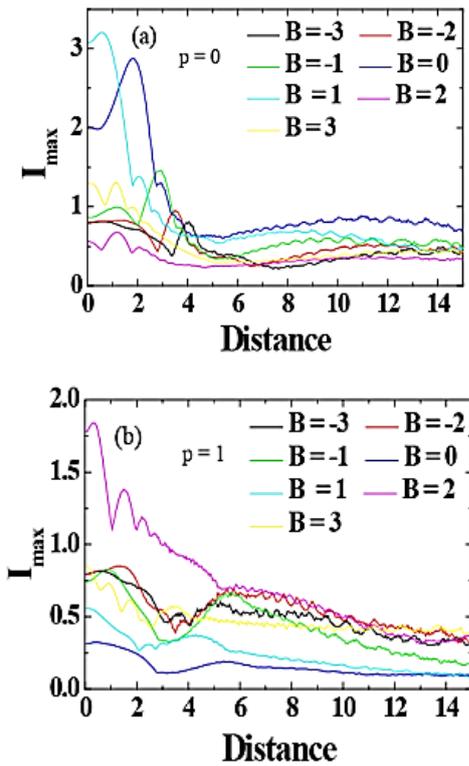


Fig. 4. The maximum of normalized intensity I_{max} of in-phase (a) and out-of-phase (b) Airy pulses interacted with dark soliton pulse with the normalized propagation distance for different values of separation parameter B and phase shift parameter p

Depending on different values of p and B , the maximum intensity, oscillation frequency are also

different. It can be seen from Fig. 4 that high frequency attenuated oscillation exhibits and the maximum of normalized intensities I_{max} in in-phase Airy pulses present larger than that in out-of-phase cases. Accordingly, appropriate quintic nonlinearity can be utilized to manipulate the maximal normalized amplitude of the central soliton pulses shedding from out-of-phase Airy pulses.

4. Conclusions

In summary, we investigate the effects of separation parameter on the propagation dynamics of in-phase and out-of-phase Airy pulses interacting with bright and dark soliton pulses in optical fiber, respectively. It can be concluded that the effects of separation parameter exhibit entirely different styles for in-phase and out-of-phase Airy pulses interaction with bright and dark soliton pulses. For in-phase Airy pulses interacting with bright soliton pulse, near the pulse centre with straight propagating one central quasi-soliton pulse generated from the main lobes of in-phase Airy pulses. Furthermore, dispersion wave pulses are shed from the background of in-phase Airy pulse, appear beside the central quasi-soliton pulse and move away from the central intense quasi-soliton pulse as the propagation distance increases. It turns out that the attraction of beams in the in-phase Airy pulses and the repulsion in the out-of-phase case. Differently, for the in-phase and out-of-phase Airy pulses interacting with dark soliton pulses, only repulsion occurs in the propagation progress.

Furthermore, separation parameter has a nearly identical impact on the evolution of in-phase and out-of-phase Airy pulse interacting with bright and dark soliton pulses, showing that the larger the separation parameter, the smaller the maximal normalized peak intensity for in-phase Airy pulses. The cases reverse for out-of-phase Airy pulses. According to these interesting results, this work inspires people to exploit appropriate separation parameter and phase parameter to manipulate the Airy pulse propagation and application.

Acknowledgements

This work was supported by the National Key Research and Development Program of China (Grant numbers 2017YFB1401203, 2017YFA0700202); the National Natural Science Foundation of China (Grant numbers 61701434, 61735010 and 61675147); the Natural Science Foundation of Shandong Province (Grant numbers ZR2017MF005, ZR2018LF001); the China Postdoctoral Science Foundation (Grant number 2015M571263); the Program of Independent and Achievement Transformation plan for Zaozhuang (Grant numbers 2016GH19, 2016GH31); Zaozhuang Engineering Research Center of Terahertz; the Project Special Funding of Taishan Scholar.

References

- [1] M. V. Berry, N. L. Balazs, *American Journal of Physics* **47**, 264 (1979).
- [2] G. A. Siviloglou, D. N. Christodoulides, *Opt. Lett.* **32**, 979 (2007).
- [3] G. A. Siviloglou, J. Broky, A. Dogariu, D. N. Christodoulides, *Phys. Rev. Lett.* **99**, 213901 (2007).
- [4] J. Broky, G. A. Siviloglou, A. Dogariu, D. N. Christodoulides *Opt. Express* **16**, 12880 (2008).
- [5] G. A. Siviloglou, J. Broky, A. Dogariu, D. N. Christodoulides, *Opt. Lett.* **33**, 207 (2008).
- [6] P. Zhang, J. Prakash, Z. Zhang, M. S. Mills, N. K. Efremidis, Christodoulides, Z. Chen, *Opt. Lett.* **36**, 2883 (2011).
- [7] I. M. Besieris, A. M. Shaarawi, *Opt. Lett.* **32**, 2447 (2007).
- [8] W.-P. Zhong, M. R. Belić, T. Huang, *Phys. Rev. A* **88**, 033824 (2013).
- [9] L. Zhang, H. Zhong, *Opt. Express* **22**, 17107 (2014).
- [10] L. Zhang, J. Zhang, Y. Chen, A. Liu, G. Liu, *J. Opt. Soc. Am. B* **31**, 889 (2014).
- [11] T. Ellenbogen, N. Voloch-Bloch, A. Ganany-Padowicz, A. Arie, *Nat. Photon.* **3**, 395 (2009).
- [12] J. Baumgartl, M. Mazilu, K. Dholakia, *Nat. Photon.* **2**, 675 (2008).
- [13] A. Chong, W. H. Renninger, D. N. Christodoulides, F. W. Wise, *Nat. Photon.* **4**, 103 (2010).
- [14] D. Abdollahpour, S. Suntsov, D. G. Papazoglou, S. Tzortzakis, *Phys. Rev. Lett.* **105**, 253901 (2010).
- [15] P. Polynkin, M. Kolesik, J. V. Moloney, G. A. Siviloglou, D. N. Christodoulides, *Science* **324**, 229 (2009).
- [16] P. Piksarv, H. Valtna-Lukner, A. Valdmann, M. Lõhmus, R. Matt, P. Saari, *Opt. Express* **20**, 17220 (2012).
- [17] P. Rose, F. Diebel, M. Boguslawski, C. Denz, *Appl. Phys. Lett.* **102**, 101101 (2013).
- [18] Y. Hu, M. Li, D. Bongiovanni, M. Clerici, J. Yao, Z. Chen, J. Azaña, R. Morandotti, *Opt. Lett.* **38**, 380 (2013).
- [19] Y. Fattal, A. Rudnick, D. M. Marom, *Opt. Express* **19**, 17298 (2011).
- [20] L. Zhang, H. Zhong, Y. Li, D. Fan, *Opt. Express* **22**, 22598 (2014).
- [21] Y. Hu, A. Tehranchi, S. Wabnitz, R. Kashyap, Z. Chen, R. Morandotti, *Phys. Rev. Lett.* **114**, 073901 (2015).
- [22] X. Zhong, X. Du, K. Cheng, *Opt. Express* **23**, 29467 (2015).
- [23] Y. Zhang, M. Belić, Z. Wu, H. Zheng, K. Lu, Y. Li, Y. Zhang, *Opt. Lett.* **38**, 4585 (2013).
- [24] F. Diebel, B. M. Bokic, D. V. Timotijevic, D. M. Jovic Savic, C. Denz, *Opt. Express* **23**, 24351 (2015).

- [25] Y. Zhang, M. R. Belic, H. Zheng, H. Chen, C. Li, Y. Li, Y. Zhang, *Opt. Express* **22**, 7160 (2014).
- [26] M. Zhang, G. Huo, H. Zhong, Z. Hui, *Opt. Express* **25**, 22104 (2017).
- [27] M. Z. Zhang, T. Y. Zhang, G. W. Huo, Z. Q. Hui, Z. L. Duan, X. W. Zha, *Communications in Nonlinear Science and Numerical Simulation* **76**, 45 (2019).
- [28] M. Shen, W. Li, R. K. Lee, *Opt. Express* **24**, 8501 (2016).
- [29] B. Liu, K. Zhan, Z. Yang, *J. Opt. Soc. Am. B* **35**, 2794 (2018).
- [30] M. Shen, L. Wu, M. Gao, W. Li, *J. Phys. B: At. Mol. Opt. Phys.* **51**, 165401 (2018).
- [31] R. Driben, Y. Hu, Z. Chen, B. A. Malomed, R. Morandotti, *Opt. Lett.* **38**, 2499 (2013).
- [32] R. Driben, T. Meier, *Phys. Rev. A* **89**, (2014).
- [33] A. A. Kovalev, V. V. Kotlyar, A. P. Porfirev, *Opt. Lett.* **41**, 2426 (2016).
- [34] A. A. Kovalev, V. V. Kotlyar, A. P. Porfirev, *Phys. Rev. A* **93**, 063858 (2016).
- [35] M. Goutsoulas, V. Paltoglou, N. K. Efremidis, *J. Opt.* **19**, 115505 (2017).
- [36] M. Shen, J. Gao, L. Ge, *Sci. Rep.* **5**, 9814 (2015).

*Corresponding author: yxllj68@126.com,
tidaylover@126.com