Research on Characteristics of Propagation of Spatial Optical Solitons in Nonlocal Media

Zhong Chunxiao, Wang Jinli

Institute of Technology, East China Jiaotong University, Nanchang, Jiangxi, China

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Abstract: In recent years, with the development of information technology, requirements for communication transmission have been constantly increased. The propagation of spatial optical solitons in material transmission shows distinct characteristics, which opens a new direction for the research on development of communication transmission. Regarding non-local media, optical solitons in different types of spaces effectively expand the exploration field of soliton science and non-linear optics, thus attracting wide attention. Next, this paper will carry out a research on the characteristics of propagation of spatial optical solitons in non-local media so as to further understand their physical properties.

1. Introduction

For spatial solitons, it is important to balance the effects of diffraction and nonlinearity to produce invariant beam waveforms in transmission. Because spatial solitons share many similarities with the properties of particles, they are of vast value for all-optical information processing, all-optical routing and other aspects, thus abstracting people making researches in this field at this stage. The main contents of this study is the characteristics of propagation of spatial optical solitons in non-local media.

2. Overview of spatial optical solitons

When a continuous laser beam propagates in any evenly-distributed medium, there is always a tendency of diffraction. The smaller the width of the incident beam is, the more obvious the diffraction is. When the beam width is in the order of micron, the effect of this diffraction cannot be ignored. According to integrated optics, the beam diffraction is usually compensated in structures containing waveguide of high refractive index. At this time, the beam can serve as the guided mode of waveguide in transmission without diffraction. Also, structures similar to the waveguide can also be realized through the non-linear effect of the medium. Because the change of refractive index is mainly determined by light intensity, the incident beam can induce waveguide structures with high center and low sides. Therefore, the beam can self-trap in the basic waveguide mode, and then form spatial optical solitons. Compared with lens, the process of soliton self-trapping can be described more vividly. Diffraction always broadens the front of the beam, which acts like a concave lens. Nonlinear self-focusing effect will produce structure containing high refractive index in the center and low ones on two sides. And it always makes the beam converge in the center, acting like convex lens. When the two lens-like effects counteract each other, their beams will self-trap and form optical soliton[1].

3. Interaction between Solitons

A hot topic in this field is the interaction between two solitons, such as splitting, merging and annihilation after collision. Compared with time solitons, spatial optical solitons can move in multi-dimensions. Because of the complexity of multi-dimensional situation, the interaction between spatial optical solitons shows more complex phenomena. Without considering the specific physical mechanism, starting from the coherence of the incident beam, the spatial soliton interaction

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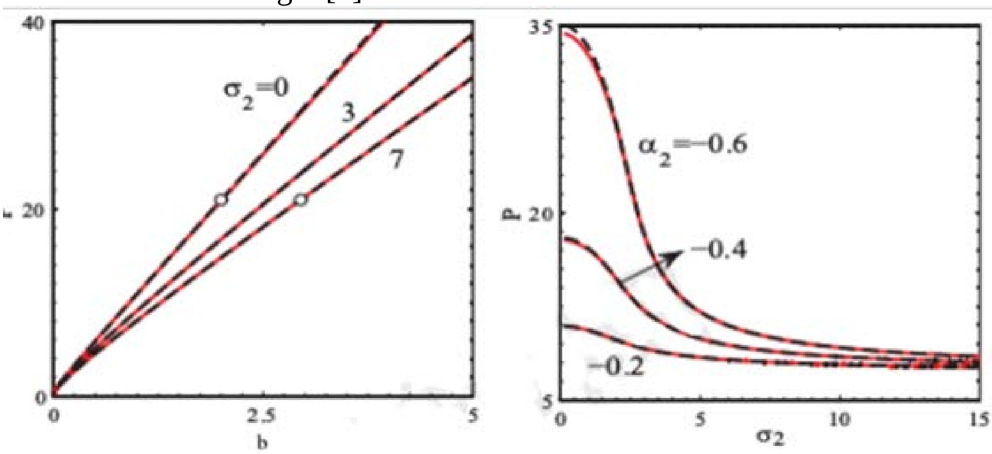
can often be divided into two types: correlated interaction and non-correlated interaction. In a self-focusing medium, the interaction between two coherent solitons is closely related to their aspects. The process of soliton interaction can be obtained in Kerr medium by means of inverse scattering. When the aspects difference between solitons is less than π/2, the two solitons are attracted to each other; when the aspects difference exceeds π/2, the two solitons are in mutual repulsion. Although this interaction also exists between temporal solitons, it is easier to understand while relating it to spatial optical solitons. When two coherent solitons overlap with each other, interference will occur. Solitons with same aspects strengthen each other's interference, while the inference of solitons with opposite aspects counter each other. Then, the distribution of light intensity will be changed, followed by distribution of local refractive index of the medium, which in turn affects the distribution of soliton light field. According to research on Kerr medium, because the refractive index is proportional to the intensity of light, two solitons with same aspects strengthen each other's light field intensity if they share common area, and the refractive index of the region will increase [2]. On the basis of geometric optics, the light tends to refract to areas of high refractive index. Therefore, the overlapping region attracts the surrounding light and makes the solitons move to the region as a whole. As a result, the two solitons tend to attract each other. Solitons with opposite aspects in the overlapping region undermine each other's light field intensity and thus decrease refractive index. As a result, the light tends to be reflected from the overlapping region and then makes the solitons move towards the region as a whole. In this situation, the two solitons have the tendency of mutual repulsion. If the aspects difference between the two solitons is neither same or opposite, the interaction between the solitons is similar to the latter situation mentioned above. It should be noted that if the non-linear medium is not a standard Kerr medium, there will be energy exchange, splitting, fusion, rotation and oscillation of soliton, as well as some other circumstances.

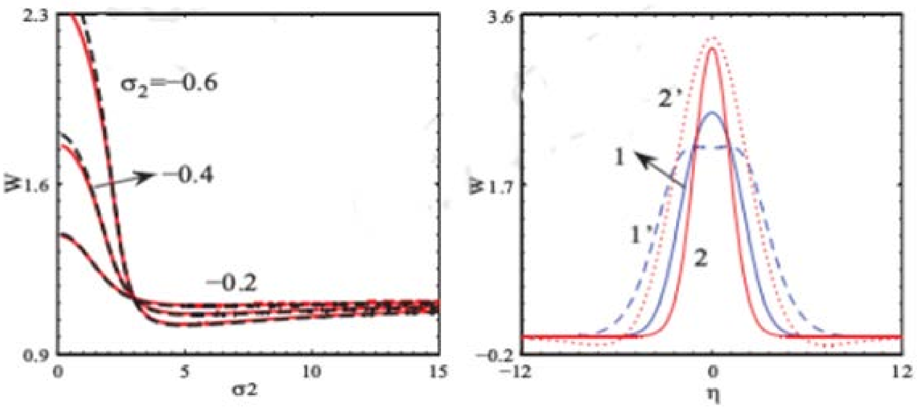
4. Characteristics of Propagation of Spatial Optical Solitons in Nonlocal Media

4.1 Spatial Bright Solitons in Competitive Nonlocal Media

In this paper, the Kerr medium model is the main model used to analyze the characteristics of propagation of bright spatial solitons in competitive nonlocal media. The solutions of the two solitons obtained by the variational method are shown in Fig. 1 and Fig. 2 respectively, which summarize the properties of basic solitons in competitive nonlocal media. According to these two graphs, it can be seen that the non-local self-defocusing and non-linearity have no effect on the main properties of basic solitons. Under the condition of constant energy flow and fixedσ2, when nonlocal lengthσ1 increases, the width of soliton increases and the amplitude decreases, which fully conforms to the characteristics of nonlocal media, i.e., nonlocal non-linear property become weaker with the increase of nonlocal length [3].



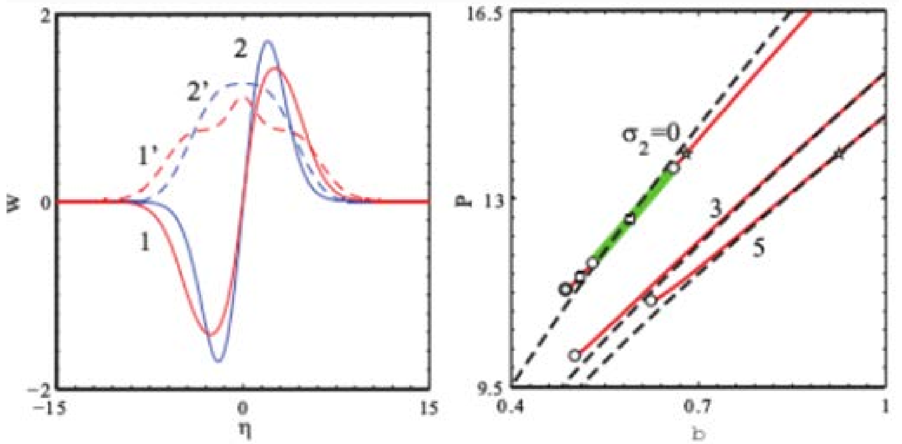
(a) Curve appear when the value of a_2 equals minus 0.2 (b) Curve P-a_2 appear when the value of b equals 1.



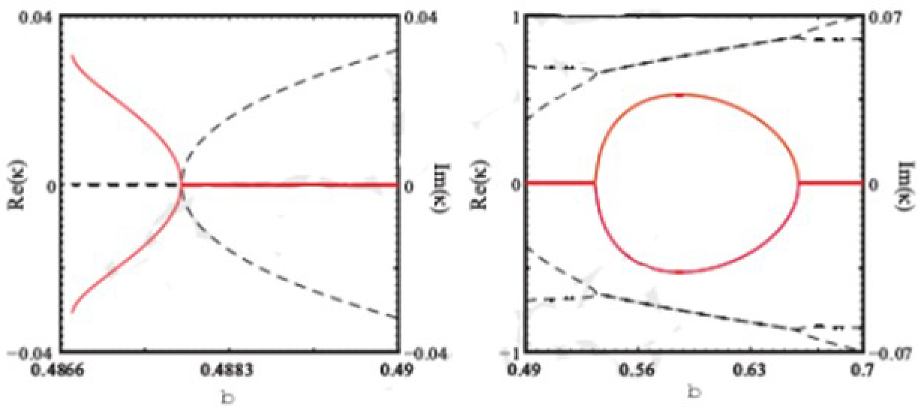
(a) Curve W-a_2 appear when the value of b equals 1. (b) Wave shape of soliton phonon (curve 1, curve 2, full curve)

Fig. 1 Properties of basic soliton in competitive nonlocal media while different parameters are involved

In Fig. 1 (a) - (c), dotted lines represent the solutions of solitons from variational method. In figure (d), dotted lines represent the distribution of the induced refractive index of solitons. In Figure (a), the dots correspond to the graph (d), 1 and 1' toσ2 = 0, and 2 and 2' toσ2 = 7.



(a) Wave shape of soliton phonon (curve 1, curve 2, full curve) (b) Curve P-b appear when the value of a2 equals to minus 0.2



(c) Key Perturbation Eigenvalues when the value ofσ2 equals to 0. (d) Key Perturbation Eigenvalues when the value ofσ2 equals to 0.

Figure 2 Properties of Dipole soliton in competitive nonlocal media when different parameters are involved

In Figure 2 (a), dotted lines represent the distribution of induced refractive index of soliton. In Figure 2 (b), dotted lines correspond to the results of variational method, and the dots represent the transition points of soliton stability. Red lines indicate stability, green lines and thick lines indicate instability. Pentagonal stars correspond to changes of solitons in graph (a).

Fig. 1 is a summary of the properties of basic solitons in competitive nonlocal media, from which it can be inferred that the nonlinearity of nonlocal self-defocusing does not affect the main properties of basic solitons. In the case of constant energy flow and fixed σ2, when nonlocal length σ1 increases, the width of soliton increases and the amplitude decreases, which fully conforms to the characteristics of nonlocal media, i.e., nonlocal non-linear property gets weaker with the increase of nonlocal length. The existence curve of solitons in Fig. 1 (a), P-b curve, satisfies the condition that d P/db > 0. The determination of the stability of some basic solitons by VK principle is still limited to the non-linear case and has not been proved in the non-local model. After rigorous linearity and stability analysis based on the results of corresponding formula, it is determined that the VK principle can guarantee the stability of basic solitons in competitive nonlocal Kerr media, that is to say, it presents a stable state in the whole existence interval. It can be seen from Fig. 1 (b) that with fixed propagation constant, the basic soliton energy flow decreases with the increase of nonlocal length σ2 [4].

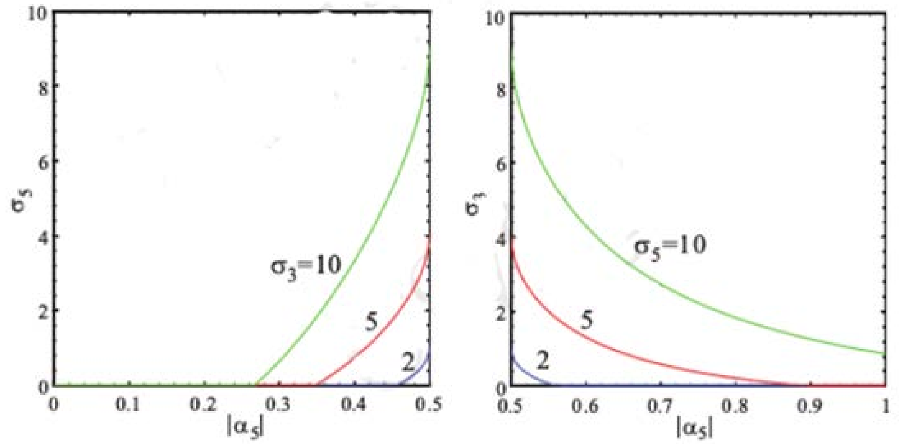
Figure 2 summarizes the properties of dipole solitons in competitive nonlocal media. The structure of the dipole soliton waveguide can be seen from Fig. 2 (a). Whenσ2 < σ1, the center of the waveguide exists sharp protuberance; whenσ2 >σ1, it is similar to the basic soliton, and its waveguide still has a negative tail. Fig. 2 (b) is the curve of dipole soliton with different non-local corresponding lengths of self-defocusing. It can be seen that the energy flow P of dipole soliton is a monotonic increasing function of propagation constant B in a large range, and becomes a decreasing function when it approaches the lowest threshold. But the soliton stability can not be judged by VK principle. The threshold of minimum propagation constant of dipole soliton varies withσ2, which indicates that competitive nonlocality has a great influence on the stability of dipole soliton. Whenσ2= 0 or within a certain parameter range, additional unstable intervals will appear, which correspond to the rough line in Fig. 2 (b). The eigenvalue spectrum of soliton perturbation can be calculated by means of linear stability to determine the instability type of dual soliton. Fig. 2 (c) and 2 (d) are the curves of change of eigenvaluest most relevant to non-linearity with the change of propagation constant b. For example, in Figure 2 (c), when the propagation constant of soliton is close to the threshold of the lowest propagation constant, pure imaginary number of the eigenvalue is obtained from the unstable interval, which means that the exponential type of soliton is unstable. When the soliton propagation constant is in the extra unstable interval, the eigenvalue is a pure imaginary number type whose real part is not zero, which corresponds to the instability of soliton oscillation. Through the validation of the above linear stability analysis results, as well as the study of soliton stability and robustness, the soliton evolution is simulated numerically by using the transmission model value of split beams with standard finite difference. And by adding 10% white noise to each soliton solution, it can be found that the simulation results are in good agreement with the stability analysis results.

4.2 Dark Solitons in Competitive Nonlocal Media

Advanced nonlinear response exists widely in nonlinear media. Kerr model is generally used in the study, which is only approximate to the actual problem. Saturated nonlinear medium is the most important type and mostly taken for study in local media and advanced nonlinearity media. Similar to bright solitons, dark solitons are also fundamental solutions from the nonlinear Schrodinger equation. Dark solitons mainly exist in the self-defocusing medium and have typical asymmetric aspects. They propagate at a certain speed in the background of plane waves [5].

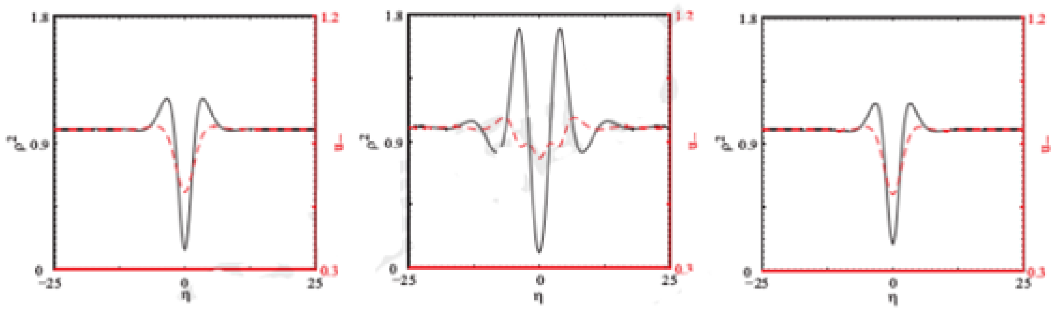
Similar to the above-mentioned competitive non-local Kerr media, Fig. 3 (a) and 2 (b) respectively show the stable intervals of planar wave modulation in the fixedσ3NCQ model (I) and the fixedσ5NCQ model (II). According to the observation of the two models, the unstable interval will widen with the increase of the nonlocal length of the self-defocusing non-linear component in the model. This is closely related to the above-mentioned nonlocal nonlinearity, that is, the nonlinearity intensity decreases with the increase of nonlocal length, but the maximum velocity of dark solitons is restricted by the intensity of nonlinearity. When non-linear length and the non-local length of the self-defocusing non-linear component is fixed, the maximum velocity of the soliton is an increasing function of the non-local length of the self-focusing component.

The distribution of soliton amplitude can be obtained from Newton's iteration formula, and the distribution of spatial integral can be obtained by numerical integration formula. In order to verify the stability of dark solitons, the characteristics of propagation of dark solitons are studied in this paper. The propagation of dark solitons is simulated by means of symmetrically distributed Fourier beams. However, it should be noted that the numerical changes of Fourier transform can only solve the symmetric distribution function accurately. In the actual simulation, two solitons with the same phase should be introduced, and they should have a wide distance, so as to eliminate the overlap of soliton wave shapes [6].

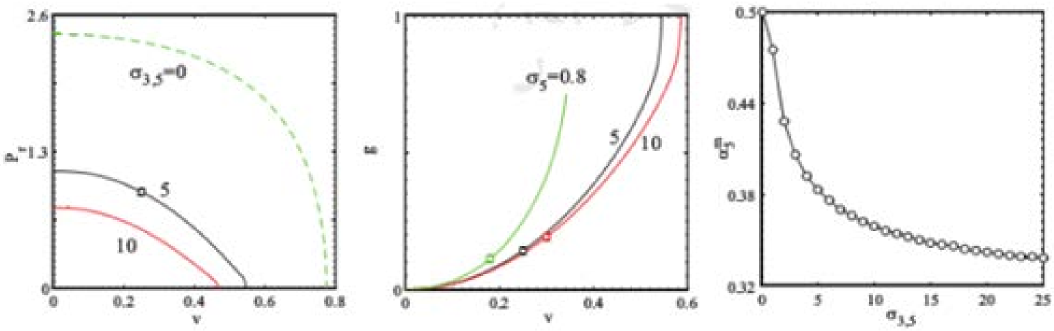


(a) NCQ Model (I) (b) NCQ Model (II)

Fig. 3 The interval of instability parameters of instability of plane wave modulation in NCQ medium. The plane wave above the curve is modulated to stable.



(a) Soliton wave shape when$\sigma_{3.5}$ equals to 5. (b) Soliton wave shape when σ3.5 is at (5, 0.8) (c) Soliton wave shape when σ3.5 is at (5, 10)



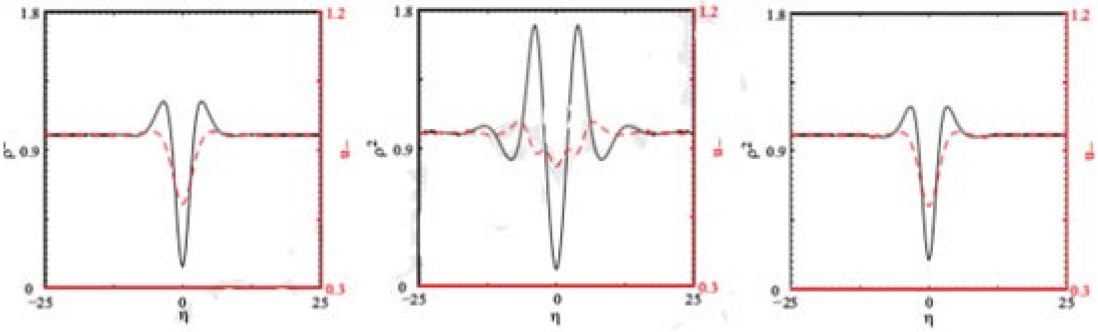
(d) Curve Pr – v (e) Curve g – v (f) Area of soliton

Figure 4 Dark soliton properties in NCQ model (I)

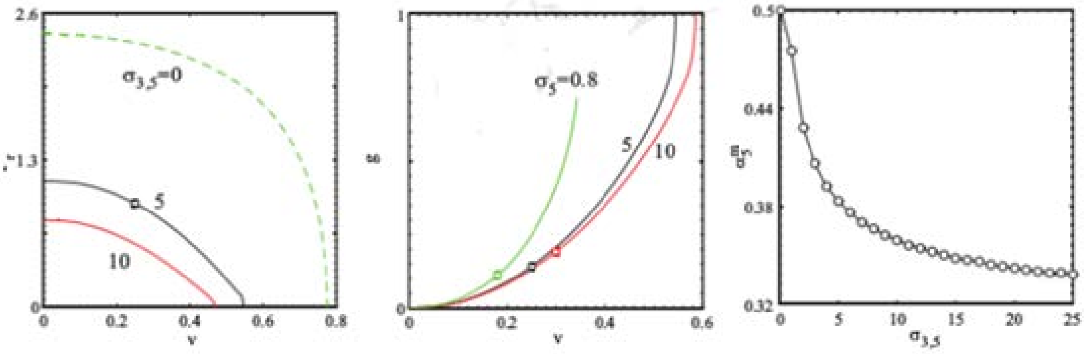
In Fig. 4 (a) - (c), the real line and the dashed line represent the actual distribution of the soliton intensity and the induced refractive index, respectively. In Figures 4 (d) and (e), the square points correspond to the solitons in Figure 4 (a) - (c). Other parameters are: (a) - (e) the existence of alpha 5 = 0.2, (e) _3 = 5.

Figure 3 is a summary of the properties of dark solitons in NCQ model (I). It is similar to dark solitons in non-local Kerr media. Its non-local effects have a significant impact on the wave shape and maximum velocity of dark solitons. As shown in Fig. 4 (a) - c, the intensity and phase space of dark solitons are distributed on both wings and exhibit multiple oscillation structures. Similar to local media, soliton size energy Pr is still a monotonic increasing function of soliton velocity, as shown in Figures 4 (d) and 4 (e). By plotting the spatial distribution of soliton waveforms and refractive index in figs. 4 (b) and (c) in the case ofσ3≠σ5, the nonlocal scale mismatch can be found, especially whenσ3 > σ5, which results in significant changes of the shape and maximum velocity of soliton.

The normalized momentum increases monotonously with the soliton velocity v, which indicates that dark solitons may be stable. A large number of simulation results also confirm the stability of dark solitons, despite that the side lobes of the solitons show unstable state when the speed is very high. Moreover, the mismatch of nonlocal length between two non-linear components does not affect the soliton stability, only increasing the oscillation of side lobes on soliton wings [7].



(a) Soliton wave shape when σ 3.5 equals to 5. (b) Soliton wave shape when σ 3.5 is at (5, 0.8) (c) Soliton wave shape when σ 3.5 is at (5, 10)



(d) Curve Pr – v (e) Curve g – v (f) Area of soliton

Figure 5 Bright soliton properties in NCQ model (I)

In Fig. 5 (a) and (b), alpha 5 = 0.4, σ3= 5 andσ5 = 5. The solid line and the dashed line represent the distribution of the soliton's light intensity and its induced refractive index, respectively. In Fig. 5 (c) - (f), the blue dotted line indicates that the corresponding local non-linear medium σ3,5 equals to 0. In Fig (f), solitons are stable in the region covered with dots when they are under the region of square points.

Fig. 5 summarizes the characteristics of dark bright solitons in the competitive NCQ model, from which it can be seen that the oscillation of both wings of dark bright solitons is weaker than that of dark solitons. Dark bright solitons exhibit intense oscillation only when they approach the maximum velocity. The non-local effect will result in the decrease of the soliton intensity amplitude and the maximum soliton velocity, especially when the intensity of self-focusing component alpha 5 is small. When the dark soliton velocity is small, it is similar to the local CQ medium. The soliton-induced refractive index distribution is typical W-shaped waveguide structure, which implies that the soliton is in an unstable state. When the velocity of dark soliton is large, the refractive index distribution induced by soliton changes into a single waveguide structure, and the dark bright soliton may present a stable state.

5. Conclusion

In summary, the characteristics of basic solitons and dipole solitons in competitive nonlocal media with different nonlocal lengths and the transmission characteristics of dark solitons in competitive nonlocal media are studied by using corresponding models. Further study is still needed in order to promote their potential value.

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