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Straight line shifts of time-domain trajectories of soliton pulses with initial first-order phase modulation in optical fibers

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ABSTRACT

The nonlinear propagation of hyperbolic secant soliton optical pulses with initial first-order phase modulation in the anomalous dispersion regions of optical fibers are investigated numerically. The corresponding evolutions of pulse shapes and spectra are provided for different soliton order and phase modulation parameters. The results show that, in the time domain, the initially first-order phase modulation can make the soliton pulse shift towards the pulse leading or trailing edges along a straight line with the pulse shape profile and its breather evolution behavior unchanged. Correspondingly, in the frequency domain, the initial first-order phase modulation can make the pulse spectrum exhibit red-shifting or blue-shifting phenomenon with the pulse spectrum profile and its breather evolution behavior unchanged. The larger the absolute value of the phase modulation parameter, the larger the shifting. While for the same phase modulation parameter, both the fundamental- and higher-order solitons exhibit the same shifting. These results may be potentially applied in manipulating the time-domain trajectories of the solitons as well as their corresponding frequency-domain positions by engineering the initial first-order phase modulation parameters of the solitons.

1. Introductions

As an important research content of nonlinear physics, solitons are ubiquitous in nature and have been observed in many nonlinear systems in different physical branches. In optical fibers, it is quite familiar to us that the hyperbolic-secant shaped fundamental and higher-order bright optical solitons are supported to exist in the anomalous dispersion and positive Kerr nonlinearity regimes. Optical solitons, especially the fundamental ones, are of great engineering importance in high speed and large capacity soliton optical communication systems due to their unique nonlinear propagation properties of shape-preserving or periodical shape-recovering [1]. In practice, however, as our recent work [2] and Ref. [1] have pointed out that, the actual input pulse may not exactly satisfy the condition of an optical soliton in terms of its shape, pulse width, initial phase, or peak power. Thus, one may ask how about the nonlinear evolution properties of these soliton-deviated optical pulses. Such questions also involve mathematically the initial value problems of nonlinear Schrödinger equation and physically the soliton stability or soliton perturbation and have triggered special research interests of researchers.

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Previous research has investigated the effects of the initial shape deviation [2], initial pulse width or peak power deviation (manifesting as the initial soliton order deviation) [3], initial phase deviation [4–11] on the nonlinear propagation properties of the soliton-deviated pulses. For the cases of the initial soliton order deviation, previous reports indicate that the pulse may adjust itself and evolve asymptotically into a standard soliton. The pulse has to experience very long asymptotic evolution distance before the final soliton formation. Of course, the initial soliton order must be larger than 0.5, otherwise, no solitons can be formed eventually. For the case of the initial shape deviation, taking the Gaussian and super-Gaussian optical pulses for example, our recent work reveals that, both their pulse shapes and spectra exhibit interesting damped oscillation behavior with decreasing oscillation amplitude for very long distance, which is quite similar to the long-distance asymptotic evolution behavior just mentioned above [2]. As for the initial phase deviation, which means that the input hyperbolic-secant pulse has the initial frequency chirp or the initial phase modulation, a large amount of studies has been made previously [4–11]. The results show that the initial linear frequency chirp or the initial second-order phase modulation is not only detrimental to the soliton formation but also causes energy loss due to the dispersion wave shedding away from the main pulse. Thus, practically speaking, the initial phase modulation is generally thought to be minimized as much as possible. However, we should note that these reports mainly focus on the case of the initial second-order phase modulation or initial linear frequency chirp. To our best knowledge, up to now, we have not seen the reports on the nonlinear propagation of the hyperbolic-secant pulse with the initial first-order phase modulation. In comparison to the initial second-order phase modulation which is also called the initial linear frequency chirp, the initial first-order phase modulation here can also be correspondingly referred to as the initial constant frequency chirp. Hence, here comes the question, namely, how the initial first-order phase modulation affects the nonlinear propagation properties of the fundamental and higher-order hyperbolic-secant soliton pulses and whether it is beneficial or detrimental to the soliton formation. To make these things clear, we numerically study the effects of the initial first-order phase modulation on the nonlinear evolutions of the fundamental and higher-order hyperbolic-secant soliton pulses in the anomalous dispersion regime of the single-mode optical fiber in detail.

2. Calculations and discussions

The standard nonlinear propagation model in the anomalous dispersion regime is of the following form

$$i\frac{\partial u}{\partial \xi} + \frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = 0 \tag{1}$$

Where u, τ, and ξ are respectively dimensionless complex envelope of the optical field, normalized time, and the normalized propagation distance.

The initial optical pulse here is the hyperbolic-secant pulse and takes the following form

$$u(0,\ \tau) = N\ \mathrm{sec}\,h(\tau)\quad \exp\quad (-i\,b\,\tau) \tag{2}$$

Where N is the order number which is closely related to the pulse width or peak power and b denotes the first-order phase modulation parameter. According to Eq. (2), we can numerically solve the nonlinear propagation equation and obtain its nonlinear evolution in terms of its shape and spectrum. In the following calculation, the amplitudes of the pulse shape and spectrum are respectively normalized as $U = \ |u|\,/\,u_{0m}$ and $S = \ |\tilde{u}|\ \ /\,\tilde{u}_{0m}$. And $\tilde{u}$ represents the Fourier transform of u. $u_{0\mathrm{m}}$ and $\tilde{u}_{0m}$ are respectively the maximum values of $|\,u(0,\,\tau)\,|$ and $|\,\tilde{u}(0,\,\nu)\,|$. ν stands for the frequency.

Fig. 1 shows the contour maps of shape evolutions of the hyperbolic-secant soliton pulses for different parameters N and b. In the figure, the parameter z_0 is the soliton period. For the case of $b = 0$, which corresponds to the standard soliton condition, as shown in Fig. 1g_1–1g_3, we can observe the familiar evolution behaviors of shape-preserving and periodical shape-recovering for the fundamental and higher-order solitons, respectively. The larger the soliton order N, the more sub-pulses the soliton breaks into. When the initial input soliton pulses are first-order phase modulated ($b \neq 0$), one can obviously see that, the time-domain trajectories of the pulses shift toward the pule leading and trailing edges along straight lines for $b > 0$ and $b < 0$, respectively. Furthermore, the figure also clearly reveals that, the larger the absolute value of the phase modulation parameter, the larger the shifting. Besides, when the phase modulation parameter is the same, both the fundamental- and higher-order solitons exhibit the same shifting. In the meantime, however, at the same distance, the pulse shape profiles remain the same as those of the $b = 0$ cases. Moreover, the nonlinear evolution properties of shape-preserving and periodical splitting and shape-recovering respectively for the fundamental and higher-order solitons also keep unchanged. That is to say, in the time domain, the existence of the first-order phase modulation can only modify the temporal positions of the solitons.

Corresponding to the pulse shape evolutions, we also provide the contour maps of spectra evolutions for different parameters N and b as shown in Fig. 2. Obviously, when there are no phase modulations, the spectra are familiar symmetric ones with their symmetric centers being zero as shown in Fig. 2g_1–g_3. As their time domain evolutions, the spectra for the fundamental and higher-order solitons are also respectively shape-preserving and periodical splitting and shape-recovering. While the existence of the initial first-order phase modulation makes the spectrum exhibit whole blue-shifting and red-shifting for $b < 0$ and $b > 0$, respectively. Similarly, the larger the absolute value of the phase modulation parameter, the larger the spectral shifting. For the same value of b, both the fundamental- and higher-order solitons exhibit the same spectral shifting. Furthermore, at the same distance, the spectra profiles remain the same as those of the $b = 0$ cases. As their time domain