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Transition, coexistence, and interaction of vector localized waves arising from higher-order effects

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HIGHLIGHTS

- Vector rogue wave properties induced by higher-order effects are studied.
- A transition between vector rogue waves and solitons is obtained.
- The link between the transition and modulation instability (MI) is demonstrated.
- The coexistence of vector solitons and breathers coincides with the MI features.
- An annihilation phenomenon for the vector two w-shaped solitons is presented.

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ABSTRACT

We study vector localized waves on continuous wave background with higher-order effects in a two-mode optical fiber. The striking properties of transition, coexistence, and interaction of these localized waves arising from higher-order effects are revealed in combination with corresponding modulation instability (MI) characteristics. It shows that these vector localized wave properties have no analogues in the case without higher-order effects. Specifically, compared to the scalar case, an intriguing transition between bright–dark rogue waves and w-shaped–anti-w-shaped solitons, which occurs as a result of the attenuation of MI growth rate to vanishing in the zero-frequency perturbation region, is exhibited with the relative background frequency. In particular, our results show that the w-shaped–anti-w-shaped solitons can coexist with breathers, coinciding with the MI analysis where the coexistence condition is a mixture of a modulation stability and MI region. It is

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interesting that their interaction is inelastic and describes a fusion process. In addition, we demonstrate an annihilation phenomenon for the interaction of two w-shaped solitons which is identified essentially as an inelastic collision in this system.

1. Introduction

Vector rogue waves are crucial to the understanding of rogue wave phenomena in a variety of complex multicomponent coupled-wave systems, including crossing sea [1,2], nonlinear optics [3], multi-species condensates [4], and finance [5]. It has been demonstrated that vector rogue waves exhibit a richer structure than scalar ones, such as dark rogue waves [6–8], four-petaled rogue waves [9], interactions between rogue waves and other nonlinear waves [10–13], coexistence of rogue waves with different structures [13], and others [14–16]. From the physical point of view, the underlying mechanism is based on the changes in the properties of modulation instability (MI) with the cross-phase modulation [7,8]. In particular, significant progresses have been made on the exact relation between vector rogue waves and MI [7]. It shows that rogue waves exist only in the zero-frequency MI subregion [7]. These results open a venue into studying rich properties of vector rogue waves in combination with MI. Motivated by this fact, we attempt to investigate interesting features of vector rogue waves arising from higher-order effects based on the corresponding MI characteristics.

Rogue waves with higher-order effects have already attracted significant interest in order to model rogue wave phenomena in a more accurate way in reality [17–20]. In fiber optics, for transmitting the ultrashort pulses, which are in the femtosecond regime, the higher order effects such as the third order dispersion, self-steepening, and delayed nonlinear response should be considered [21]. Recent studies have demonstrated that vector rogue waves can suffer from these higher-order effects [22,23]. However, the features of vector rogue waves arising from higher-order effects have not been revealed, to our knowledge. Nevertheless, in contrast to the case without high-order effects, the MI exhibits some new characteristics induced by the higher-order effects [see Fig. 1], which potentially yields different and significant vector rogue-wave dynamics.

In this paper, we go beyond previous studies [22,23], by considering the transition, coexistence, and interaction of vector localized waves on continuous wave background arising from higher-order effects. Our treatment below goes as follows. In Section 2, we display the striking MI characteristics induced by the higher-order effects. In Section 3, we present the corresponding interesting localized-wave dynamics, including the transition between bright–dark rogue waves and w-shaped–anti-w-shaped solitons, the coexistence and inelastic interaction between w-shaped–anti-w-shaped solitons and breathers, and the annihilation for the two w-shaped soliton interaction. The final section is reserved for conclusions.

2. Model and MI characteristics

We address this problem through ultrashort pulses propagation in the femtosecond regime for a two-mode nonlinear fiber, where the higher-order effects, such as third-order dispersion, self-steepening, and delayed nonlinear response must be taken into account. In this case, the characteristics of the vector optical rogue waves can be described by the completely integrable coupled Hirota (CH) model [24,25], which involves the higher-order perturbation effects above. In dimensionless form, the CH model reads:

$$iu_{jz} + \frac{1}{2}u_{jtt} + \left(\sum_{l=1}^{2}|u_l|^2\right)u_j + i\beta\left[u_{jttt} + 3\left(\sum_{l=1}^{2}|u_l|^2\right)u_{jt} + 3\left(\sum_{l=1}^{2}u_l^* u_{lt}\right)u_j\right] = 0 \qquad (1)$$