Collision Dynamics of Solitons in a Grating Assisted Semilinear dual-core System with Phase Mismatch

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***Abstract*—The collision dynamics between two counter-propagating moving Bragg grating solitons and their outcomes in a model of semilinear dual-core Bragg-grating coupler with phase mismatch are investigated. The influence of gratings phase mismatch on the collision outcomes is also discussed.**

***Index Terms*—Bragg grating solitons; Collison dynamics; Phase mismatch.**

I. INTRODUCTION

Since the 1980s, fiber Bragg gratings (FBGs) have been the subject of much research and interest thanks to their potential applications in all-optical sensing, filtering and signal processing [1, 2]. One of the main characteristics of the FBGs is that due to the resonant reflection of counter propagating waves on the fiber Bragg gratings (FBGs), an intense effective dispersion induced, which may be up to six orders of magnitude more than the conventional bare fiber [3, 4]. When the FBGs are operated in the nonlinear regime, the grating induced strong effective dispersion can be counterbalanced by the nonlinearity of the medium leading to the formation of Bragg grating (BG) solitons [5, 6]. The intriguing characteristics of BG solitons, including rich nonlinear dynamics and intrinsic stability properties, accelerates both experimental [7, 8] and theoretical [9, 10] research by considering different photonic structures for numerous novel optical applications, such as optical fiber-based sensor, optical filtering and switching, pulse compressor and dispersion compensators [11]. It should be noted that BG (or Gap) solitons have been theoretically predicted in other optical systems such as nonuniform gratings [12], photonic crystals [13, 14], and microcavities with a periodic potential [15].

One of the attractive features of the BG solitons is that they can exhibit reduced light speed during propagation ranging from zero to the light speed in the medium. This fascinating feature of BG solitons paves the way to generate slow (or stopped) optical pulse in the medium, which is applicable in different optical slow light-based applications, such as all-optical signal processing, optical logic gates, delay lines and buffers [11]. BG solitons with as low as $23\,\%$ of the group velocity have been observed experimentally [16]. Theoretically, it has been reported that an well controlled localized defect in a Bragg grating structure can trap the soliton, which allows to generate a very slow optical BG solitons [17]. Other theoretical investigations have found that collision between two counter-propagating moving solitons can form slow or zero velocity BG solitons [18, 19]. Moreover, the collision dynamics between two moving BG solitons in different photonic structures have been investigated to manipulate the light waves for different novel optical applications [20].

In this paper, we analyze the collision dynamics of moving BG solitons in a semilinear dual-core system, where Bragg gratings are written on the both cores with phase mismatch.

II. SYSTEM MODEL

The propagation of optical waves in a semilinear dual-core system, where Bragg gratings are written on both cores with a phase mismatch can be modeled by the following set of normalized coupled-mode equations for the forward $\{u(x,t),\, \phi(x,t)\}$ and the backward $\{v(x,t),\, \psi(x,t)\}$ propagating waves in the $\{nonlinear,\, linear\}$ cores:

$$\begin{aligned} iu_t + iu_x + \left(|v|^2 + \frac{1}{2}|u|^2\right)u + v + \kappa\phi &= 0, \\ iv_t - iv_x + \left(|u|^2 + \frac{1}{2}|v|^2\right)v + u + \kappa\psi &= 0, \\ i\phi_t + i\,c\phi_x + \psi\, e^{i\frac{\theta}{2}} + \kappa u &= 0, \\ i\psi_t - i\,c\psi_x + \phi\, e^{-i\frac{\theta}{2}} + \kappa v &= 0, \end{aligned} \tag{1}$$

where, θ $(0 \leq \theta \leq 2\,\pi)$ and κ represent the strength of phase mismatch and linear coupling coefficient, respectively. Also, the relative group velocity in the linear core is represented by c, while in the nonlinear core it is set equal to 1.

In order to find the solutions of moving BG solitons, it is necessary to transform Eqs. (1) into the moving coordinates, $\{X, T\} = \{x - \delta\, t,\, t\}$. The soliton solutions are then obtained using numerical techniques. Here, δ is the normalized velocity of soliton and $\delta = 1$ represents the velocity of light in the medium. We have found that when both δ and c are non-zero, only the central gap contains the moving BG solitons. The central gap expands (shrinks) with the increasing θ (δ) for the fixed values of δ and c $(\theta \text{ and } c)$. There is a cut-off value of $\delta_{cr} < 1.0$, over which no moving BG solitons exist in the central gap. The value of δ_{cr} increases with the increasing vslues of θ.

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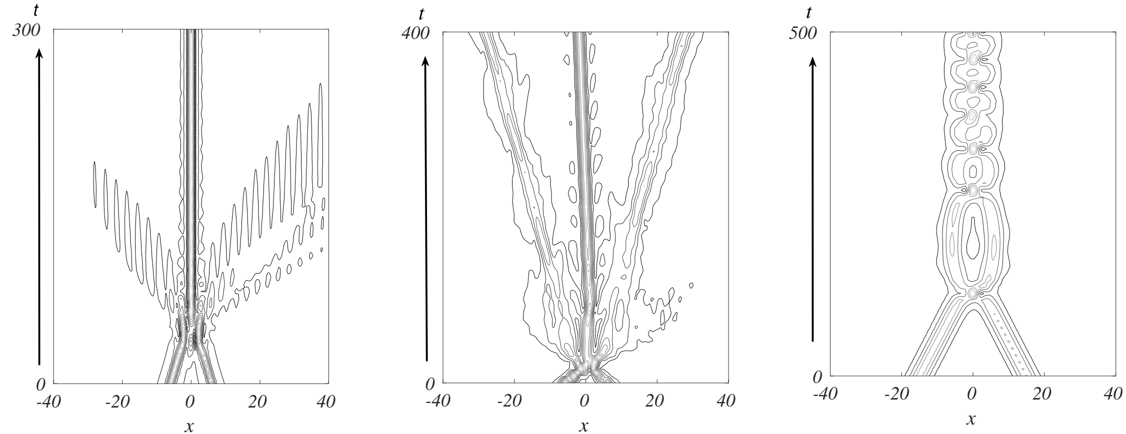

(a) (b) (c)

Fig. 1. Outcomes of the collision of initially in-phase solitons at $c = 1$: a) merger into a quiescent soliton for $\delta = 0.1$, $\Omega = 0.75$, $\kappa = 1.0$, $\theta = 2\,\pi$, $\Delta x = 12$; b) generation of three solitons (one quiescent and two moving solitons) for $\delta = 0.3$, $\Omega = 0.23$, $\kappa = 1.0$, $\theta = 1.1\,\pi$, $\Delta x = 12.0$; c) temporary bound-state followed by merging for $\delta = 0.1$, $\Omega = 0.86$, $\kappa = 0.1$, $\theta = 2\,\pi$, $\Delta x = 30$. Only the u-component is shown.

III. COLLISIONS OF MOVING BG SOLITONS

To observe the collision dynamics between two in-phase counter-propagating moving BG solitons with initial separation (Δx), we have used systematic numerical simulations. It has been observed that the outcomes of in-phase collision depend on solitons velocity (δ), frequency detuning (Ω), phase mismatch (θ), coupling coefficient (κ), relative group velocity (c) and initial separation (Δx). Several interesting outcomes have been identified through out our investigations, such as separation of colliding solitons with increase and decrease velocities, merger into a single zero velocity soliton, generating three solitons (one quiescent and two moving solitons), temporary bound state followed by separation and merging, and completely destruction of the colliding solitons. Some of the important outcomes obtained during collisions are shown in Fig. 1, such as merging into single quiescent or zero-velocity soliton [see. Fig. 1(a)], three soliton formation where one of them is quiescent soliton [see. Fig. 1(b)] and temporary bound-state followed by a quiescent soliton [see. Fig. 1(c)]. It is noteworthy that in cases of the merger (i.e. Fig. 1(a)) and the temporary bound state soliton (Fig. 1(c)), the amount of radiation is significantly smaller than that for the three soliton formation (Fig. 1(b)).

A noteworthy finding being that the increasing phase mismatch effect can expand the merging region significantly in terms of Ω. Also, phase mismatch effect creates sidelobes on the tails of moving BG solitons, which affects the collision dynamics significantly. This is currently under investigation.

REFERENCES

[1] R. Kashyap, *Fiber Bragg gratings* (Academic Press, Boston, 2010), 2nd ed.
[2] H. Cao, X. Shu, J. Atai, A. Gbadebo, B. Xiong, T. Fan, H. Tang, W. Yang, and Y. Yu, Opt. Express **22**, 30442 (2014).
[3] P. Russell, J. Mod. Opt **38**, 1599 (1991).
[4] C. M. Desterke and J. E. Sipe, Progress in Optics **33**, 203 (1994).
[5] A. B. Aceves and S. Wabnitz, Phys. Lett. A **141**, 37 (1989).
[6] D. N. Christadoulides and R. I. Joseph, Phys. Rev. Lett. **62**, 1746 (1989).
[7] B. J. Eggleton, C. M. de Sterke, and R. E. Slusher, J. Opt. Soc. Am. B **14**, 2980 (1997).
[8] C. M. De Sterke, B. J. Eggleton, and P. A. Krug, J. Lightwave Technol. **15**, 1494 (1997).
[9] J. Atai and B. A. Malomed, Phys. Rev. E Stat. Phys. Plasmas Fluids Relat. Interdiscip. Topics **62**, 8713 (2000).
[10] Y. J. Tsofe and B. A. Malomed, Phys. Rev. E Stat. Nonlin. Soft Matter Phys. **75**, 056603 (2007).
[11] G. P. Agrawal, *Applications of nonlinear fiber optics* (Academic Press, San Diego, CA, 2001).
[12] J. Atai and B. A. Malomed, Phys. Lett. A **342**, 404 (2005).
[13] D. V. Skryabin, Opt. Express **12**, 4841 (2004).
[14] J. Atai, B. A. Malomed, and I. M. Merhasin, Opt. Comm. **265**, 342 (2006).
[15] A. Gorbach, B. Malomed, and D. Skryabin, Phys. Lett. A **373**, 3024 (2009).
[16] J. T. Mok, C. M. de Sterke, I. C. M. Littler, and B. J. Eggleton, Nat. Phys. **2**, 775 (2006).
[17] R. H. Goodman, R. E. Slusher, and M. I. Weinstein, J. Opt. Soc. Am. B **19**, 1635 (2002).
[18] W. C. Mak, B. A. Malomed, and P. L. Chu, Phys. Rev. E **68**, 026609 (2003).
[19] D. R. Neill and J. Atai, Phys. Lett. A **353**, 416 (2006).
[20] S. A. M. S. Chowdhury and J. Atai, Sci. Rep. **7**, 4021 (2017).