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Stabilizing soliton-based multichannel transmission with frequency dependent linear gain–loss

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ABSTRACT

We report several major theoretical steps towards realizing stable long-distance multichannel soliton transmission in Kerr nonlinear waveguide loops. We find that transmission destabilization in a single waveguide is caused by resonant formation of radiative sidebands and investigate the possibility to increase transmission stability by optimization with respect to the Kerr nonlinearity coefficient γ. Moreover, we develop a general method for transmission stabilization, based on frequency dependent linear gain–loss in Kerr nonlinear waveguide couplers, and implement it in two-channel and three-channel transmission. We show that the introduction of frequency dependent loss leads to significant enhancement of transmission stability even for non-optimal γ values via decay of radiative sidebands, which takes place as a dynamic phase transition. For waveguide couplers with frequency dependent linear gain–loss, we observe stable oscillations of soliton amplitudes due to decay and regeneration of the radiative sidebands.

1. Introduction

The rates of transmission of information in broadband optical waveguide systems can be significantly increased by transmitting many pulse sequences through the same waveguide [1–3]. This is achieved by the wavelength-division-multiplexing (WDM) method, where each pulse sequence is characterized by the central frequency of its pulses, and is therefore called a frequency channel. Applications of these WDM or multichannel systems include fiber optics communication lines [1–3], data transfer between computer processors through silicon waveguides [4,5], and multiwavelength lasers [6,7]. Since pulses from different frequency channels propagate with different group velocities, interchannel pulse collisions are very frequent, and can therefore lead to severe transmission degradation [1]. Soliton-based transmission is considered to be advantageous compared with other transmission formats, due to the stability and shape-preserving properties of the solitons, and as a result, has been the focus of many studies [1–3]. These studies have shown that effects of Kerr nonlinearity on interchannel collisions, such as cross-phase modulation and four-wave-mixing, are among the main impairments in soliton-based WDM fiber optics transmission. Furthermore, various methods for mitigation of Kerr-induced effects, such as filtering and dispersion-management, have been developed [2,3]. However, the problem of achieving stable long-distance propagation of optical solitons in multichannel Kerr nonlinear waveguide loops remains unresolved. The challenge in this case stems from two factors. First, any radiation emitted by the solitons stays in the waveguide loop, and therefore, the radiation accumulates. Second, the radiation emitted by solitons from a given channel at frequencies of the solitons in the other channels undergoes unstable growth and develops into radiative sidebands. Due to radiation accumulation and to the fact that the sidebands form at the frequencies of the propagating solitons it is very difficult to suppress the instability. In the current paper, we report several major steps towards a solution of this important problem.

In Refs. [8–13], we studied soliton propagation in Kerr nonlinear waveguide loops in the presence of dissipative perturbations due to delayed Raman response and nonlinear gain–loss. We showed that transmission stabilization can be realized at short-to-intermediate distances, but that at large distances, the transmission becomes unstable, and the soliton sequences are destroyed. Additionally, in Ref. [10], we noted that destabilization is caused by resonant formation of radiative sidebands due to cross-phase modulation. However, the central problems of quantifying the dependence of transmission stability on physical parameter values and of developing general methods for transmission stabilization

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against Kerr-induced effects were not addressed. In the current paper we take on these problems for two-channel and three-channel transmission by performing extensive simulations with a system of coupled nonlinear Schrödinger (NLS) equations. We first study transmission in a single lossless waveguide and investigate the possibility to increase transmission stability by optimization with respect to the value of the Kerr nonlinearity coefficient. We then demonstrate that significant enhancement of transmission stability can be achieved in waveguide couplers with frequency dependent linear loss and gain and analyze the stabilizing mechanisms. This stabilization is realized without dispersion-management or filtering.

2. The coupled-NLS propagation model

We consider propagation of N sequences of optical pulses in an optical waveguide in the presence of second-order dispersion, Kerr nonlinearity, and frequency dependent linear gain–loss. We assume a WDM setup, where the pulses in each sequence propagate with the same group velocity and frequency, but where the group velocity and frequency are different for pulses from different sequences. The propagation is then described by the following system of N coupled-NLS equations [1,10]:

$$i\partial_z\psi_j + \partial_t^2\psi_j + \gamma|\psi_j|^2\psi_j + 2\gamma\sum_{k\neq j}|\psi_k|^2\psi_j = i\mathcal{F}^{-1}(g_j(\omega)\hat{\psi}_j)/2, \tag{1}$$

where ψ_j is the envelope of the electric field of the jth sequence, $1 \le j \le N$, z is propagation distance, t is time, ω is frequency, γ is the Kerr nonlinearity coefficient, and the sum over k extends from 1 to N [14]. In Eq. (1), $g_j(\omega)$ is the linear gain–loss experienced by the jth sequence, $\hat{\psi}_j$ is the Fourier transform of ψ_j with respect to time, and $\mathcal{F}^{-1}$ is the inverse Fourier transform. The second term on the left-hand side of Eq. (1) is due to second-order dispersion, the third term describes self-phase modulation and intrasequence cross-phase modulation, while the fourth term describes intersequence cross-phase modulation. The term on the right-hand side of Eq. (1) is due to linear gain–loss. The optical pulses in the jth sequence are fundamental solitons of the unperturbed NLS equation $i\partial_z\psi_j + \partial_t^2\psi_j + \gamma|\psi_j|^2\psi_j = 0$. The envelopes of these solitons are given by $\psi_{sj}(t, z) = \eta_j \exp(i\chi_j)\mathrm{sech}(x_j)$, where $x_j = (\gamma/2)^{1/2}\eta_j(t - y_j - 2\beta_j z)$, $\chi_j = \alpha_j + \beta_j(t - y_j) + (\gamma\eta_j^2/2 - \beta_j^2)z$, and η_j, β_j, y_j, and α_j are the soliton amplitude, frequency, position, and phase.

Notice that Eq. (1) describes both propagation in a single waveguide and propagation in a waveguide coupler, consisting of N close waveguides [15]. In waveguide coupler transmission, each waveguide is characterized by its linear gain–loss function $g_j(\omega)$. The form of $g_j(\omega)$ is chosen such that radiation emission effects are mitigated, while the soliton patterns remain intact. In particular, we choose the form

$$\begin{aligned} g_j(\omega) = -g_L + \tfrac{1}{2}(g_{eq} + g_L)[&\tanh\{\rho[\omega - \beta_j(0) + W/2]\} \\ &-\tanh\{\rho[\omega - \beta_j(0) - W/2]\}], \end{aligned} \tag{2}$$

where $1 \le j \le N$, and $\beta_j(0)$ is the initial frequency of the jth sequence solitons. The constants g_L, g_{eq}, ρ, and W satisfy $g_L > 0$, $g_{eq} \ge 0$, $\rho \gg 1$, and $\Delta\beta > W > 1$, where $\Delta\beta$ is the intersequence frequency difference. We note that the condition $\Delta\beta > 1$ is typical for soliton-based WDM transmission experiments [16–20]. Fig. 1 shows typical linear gain–loss functions $g_1(\omega)$ and $g_2(\omega)$ for a two-channel waveguide coupler with $g_L = 0.5$, $g_{eq} = 3.9 \times 10^{-4}$, $\beta_1(0) = -5$, $\beta_2(0) = 5$, W=5 and $\rho = 10$ (these parameters are used

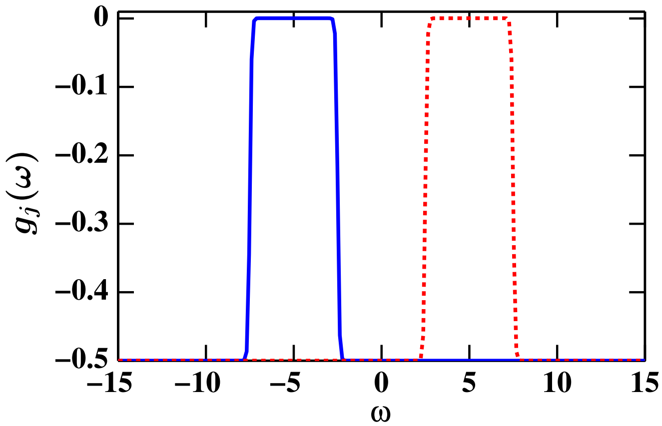

Fig. 1. An example for the frequency dependent linear gain–loss functions $g_j(\omega)$ defined by Eq. (2) in a two-channel waveguide coupler. The solid blue and dashed red lines correspond to $g_1(\omega)$ and $g_2(\omega)$, respectively. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

in the numerical simulations, whose results are shown in Fig. 8). In the limit as $\rho \gg 1$, $g_j(\omega)$ can be approximated by a step function, which is equal to g_{eq} inside a frequency interval of width W centered about $\beta_j(0)$, and to $-g_L$ elsewhere:

$$g_j(\omega) \simeq \begin{cases} g_{eq} & \text{if } \beta_j(0) - W/2 < \omega \le \beta_j(0) + W/2, \\ -g_L & \text{elsewhere.} \end{cases} \tag{3}$$

The approximate expression (3) helps clarifying the advantages of using the linear gain–loss function (2) for transmission stabilization. Indeed, the relatively strong linear loss g_L leads to efficient suppression of radiative sideband generation outside of the frequency interval $(\beta_j(0) - W/2, \beta_j(0) + W/2]$. Furthermore, the relatively weak linear gain g_{eq} in the frequency interval $(\beta_j(0) - W/2, \beta_j(0) + W/2]$ compensates for the strong loss outside of this interval and in this manner enables soliton propagation without amplitude decay. In practice, we first determine the values of g_L, W, and ρ by performing simulations with Eqs. (1) and (2) with $g_{eq} = 0$, while looking for the set that yields the longest stable propagation distance. Once g_L, W, and ρ are found, we determine g_{eq} by requiring $\eta_j(z) = \eta_j(0) = \text{const}$ for $1 \le j \le N$ throughout the propagation. More specifically, we use the adiabatic perturbation theory for the NLS soliton (see, e.g., Ref. [3]) to derive the following equation for the rate of change of η_j with z due to the linear gain–loss (2):

$$\frac{d\eta_j}{dz} = \left[-g_L + (g_{eq} + g_L)\tanh\left(\frac{\pi W}{(8\gamma)^{1/2}\eta_j}\right)\right]\eta_j. \tag{4}$$

Requiring $\eta_j(z) = \eta_j(0) = \text{const}$, we obtain the following expression for g_{eq}:

$$g_{eq} = \left\{\left[\tanh\left(\frac{\pi W}{(8\gamma)^{1/2}\eta_j(0)}\right)\right]^{-1} - 1\right\}g_L. \tag{5}$$

Since different pulse sequences propagate with different group velocities, the solitons undergo a large number of intersequence collisions. Due to the finite length of the waveguide and the finite separation between adjacent solitons in each sequence, the collisions are not completely elastic. Instead, the collisions lead to emission of continuous radiation with peak power that is inversely proportional to the intersequence frequency difference $\Delta\beta$. The emission of continuous radiation in multiple collisions eventually