Nonlinear Pulses in Dispersion-Managed Fiber-Optic Systems in Presence of High Losses

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Abstract. A dispersion managed fiber-optic system can support dynamically stable pulses - DM-solitons and two branches of stable pairs of coupled DM-solitons – lower and upper bisolitons. Using semi-analytical model, we have found the dependency of the shape of these pulses on the level of losses and other parameters of the system and have verified the validity of our findings both numerically and experimentally. The obtained data can be used to define whether a dispersion-managed fiber-optic system can be considered as the one with constant dispersion.

1. Introduction

Dispersion management is widely used in fiber-optic systems to suppress dispersive broadening of the pulses. In a dispersion-managed (DM) system optical elements with high absolute values of normal and anomalous group velocity dispersion (GVD) are combined in a periodically repeating dispersion map to minimize the average value of GVD in the system. Propagation of an electromagnetic pulse through this system is well described by Nonlinear Schrödinger Equation (NLSE).

For NLSE applied to describe the DM optical fiber system, three groups of nonlinear dynamically stable solutions have been found both numerically and experimentally. There are: dispersion-managed solitons (DM-solitons) [1], two branches of stable two-soliton anti-phase compounds - lower and upper bisolitons [2,3], and three-solitons - bound compositions of three DM-solitons [4,5]. The shape of these pulses constantly evolves during propagation over the system regaining its original shape only at the end of each dispersion map period.

This work focuses only on DM-solitons, lower and upper bisolitons. Despite stable propagation of DM-solitons has been experimentally found in lossy systems rather long time ago [1], the existence of bisolitons has been experimentally confirmed only in the experiments deliberately excluding losses [3,4]. Similarly, the dependence of the shape of DM-soliton, lower and upper bisoliton on the parameters of a DM system has been described numerically only for the case of lossless systems [2,6]. Nevertheless, losses of optical power in a typical fiber-optic communication line are substantial. Although the losses are compensated by periodically installed optical amplifiers, propagation of DM-solitons and bisolitons is strongly affected by these losses. Therefore, for possible practical applications, it is essential to take into account the effect of losses on the shape of DM-solitons and bisolitons in the DM fiber-optic systems. In particular, bisolitons can be used to increase the capacity of the existing DM long-haul fiber-optic communication lines. We can introduce lower and upper bisolitons into communication alphabet as two extra letters (correspondingly, '2' and '3') in addition to the already employed DM-soliton ('1') and empty slot ('0') [2]. Moreover, bisolitons were suggested for usage in the optical retiming scheme [7].

2. Method

To study dynamically stable pulses in lossy DM systems we solved numerically the Gabitov-Turitsyn equation [8] describing the slow dynamics of pulses in a DM nonlinear system, which is governed solely by an averaged dispersion and nonlinearity. DM-solitons, lower and upper bisolitons are solitary solutions of this equation. To find them, we adapted the existing computer algorithm [6] to account for losses.

The obtained results were verified both numerically and experimentally. To check them numerically, we have examined the propagation of the obtained pulses by solving NLSE, and found that the obtained pulses are indeed dynamically stable solutions of NLSE - they returned to their original shapes having passed any number of dispersion map periods.

To check experimentally the predictions of our computer algorithm we compared the numerically obtained solutions with ones that emerge in a particular real-world DM fiber system. The experimentally investigated line had been chosen as close as possible to the real terrestrial systems. The modelled line had the length of about 3300 km, the period length 47.3 km, and losses over the period 15.2 dB. We have shown that the relationship between the peak power and the full-width at half maximum (FWHM) of the DM-solitons generated in our experiment agrees with the one predicted by our algorithm (Fig. 1).

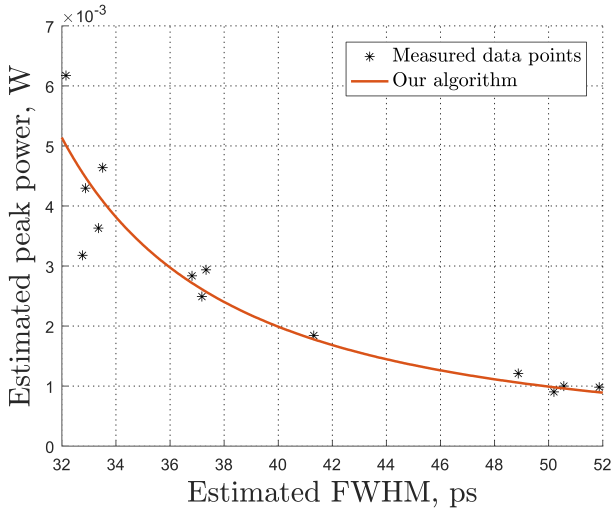

Figure 1. Comparison between the relation of estimated peak power and FWHM for experimentally measured DM-solitons and the numerically predicted ones.

3. Numerical results

Dependence of the shape of DM-solitons (lower and upper bisolitons) on parameters of a DM fiber-optic system (excepting losses) manifests itself through the dependence on the single dimensionless combination - reduced dispersion $\bar{d}_0$[2]:

$$\bar{d}_0 = \frac{2\langle\beta_2\rangle}{\gamma PL\langle\beta_2^{TF}\rangle}, \qquad (1)$$

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where $\langle\beta_2\rangle$ is the averaged GVD of the DM system, $\langle\beta_2^{TF}\rangle$ is the averaged GVD of fibers in the system with anomalous dispersion ($\beta_2 < 0$) in the DM system, γ is the effective nonlinear coefficient, P is the characteristic pulse peak power, and L is the period length of the system.

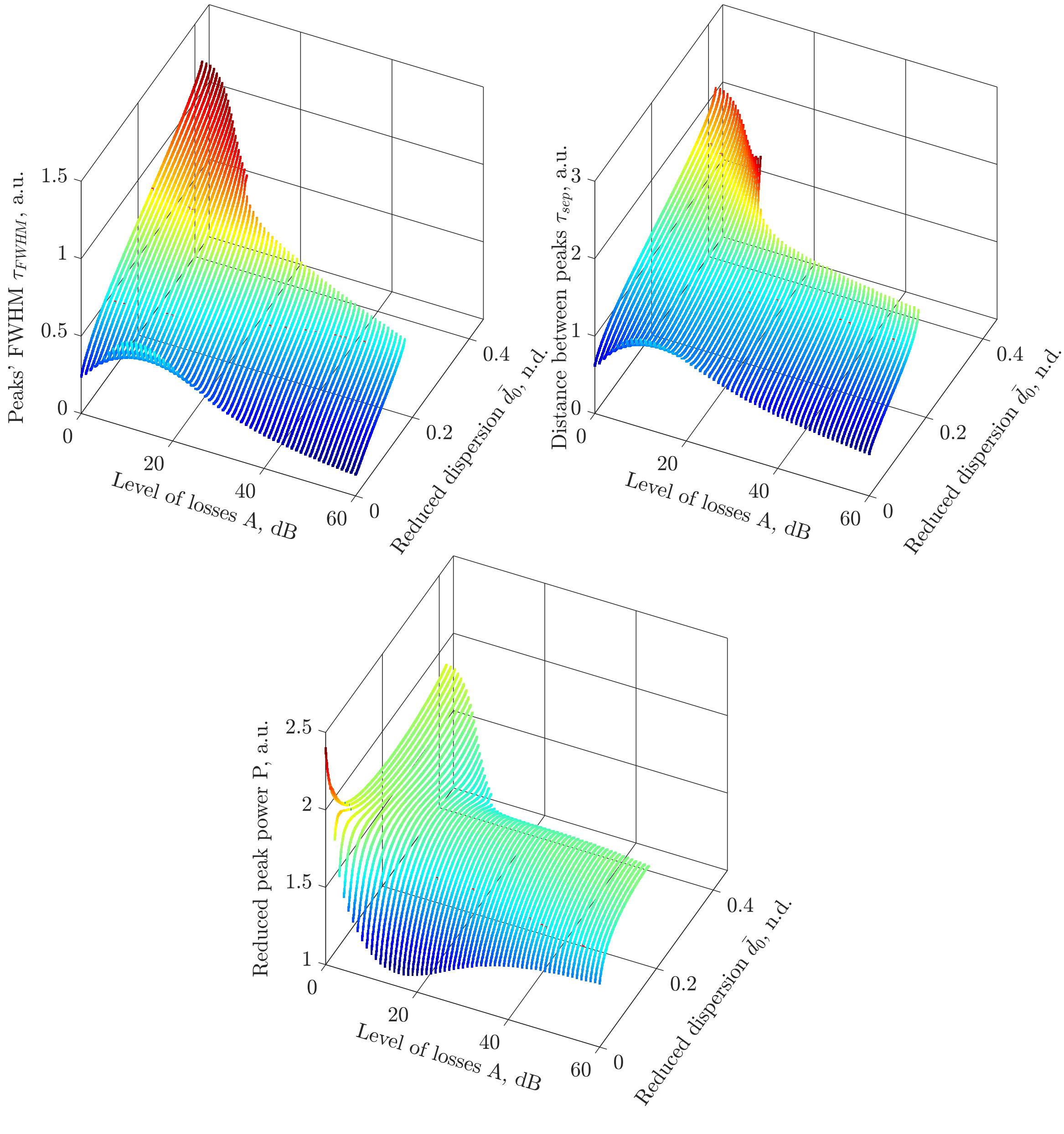

Figure 2. Dependence of the parameters describing the shape of lower bisoliton on the level of the losses on the period of DM fiber-optic system and on other parameters of the system expressed through the reduced dispersion $\bar{d}_0$. As the parameters we measured reduced peak power P and FWHM of each of the pulses forming the lower bisoliton along with the distance between the centers of mass of each of the pulses τ_{sep}.

To make conclusions about the dependence of this link on losses we studied numerically the dependence of characteristic parameters of the lower and upper bisolitons on both reduced dispersion $\bar{d}_0$ and level of losses. We examined reduced peak power P and FWHM of each of the pulses forming the bisolitons, temporal separation between the pulses τ_{sep}, and found that dependence of these parameters on reduced dispersion $\bar{d}_0$ is affected by the level of losses (Fig. 2).

$$\mathrm{P} = \max_t(|u(t)|^2)/\aleph, \quad \aleph = \frac{1-e^{-\alpha}}{\alpha}, \quad \alpha = A\frac{\ln 10}{10}; \; \tau_{sep} = \frac{\int_0^\infty dt\, t|u(t)|^2}{\int_0^\infty dt\, |u(t)|^2} - \frac{\int_{-\infty}^0 dt\, t|u(t)|^2}{\int_{-\infty}^0 dt\, |u(t)|^2}, \quad (2)$$

where $u(t)$ is the wavepacket of the pulse and t is the retarded time frame moving with the group velocity of the bisoliton, so that $t = 0$ point is always situated at the point of bisoliton antysimmetry ($u(t) = -u(-t)$).

Moreover, we have found that the position of the upper limit on the reduced dispersion $\bar{d}_0$ for which lower and upper bisolitons can stably propagate, referred to as the bifurcartion point $\bar{d}_0^{bif}$ [2], is very sensitive to the level of losses (Fig. 3). Since bisolitons are not dynamically stable solutions of NLSE with constant GVD, we suggest usage of bifurcation point $\bar{d}_0^{bif}$ as a limit on DM system parameters for which the real GVD distribution cannot be approximated by the average GVD.

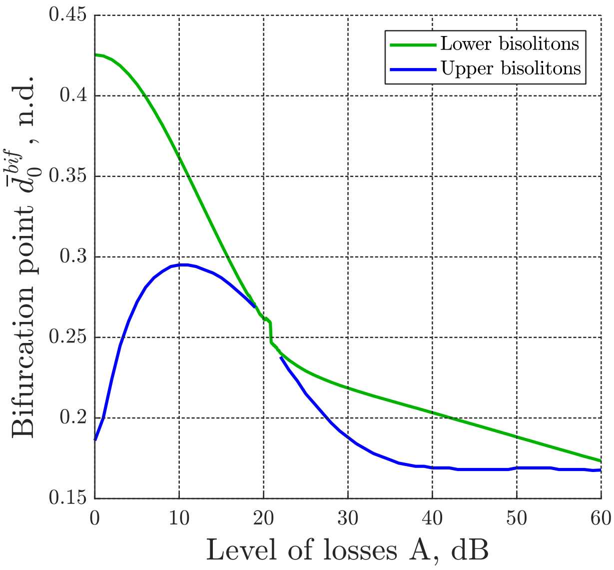

Figure 3. Dependence of the position of bifurcation point $\bar{d}_0^{bif}$ (green line) and the existence region of upper bisolitons (between green and blue lines) on the level of losses A on the period of a DM fiber-optic system. Bifurcation point $\bar{d}_0^{bif}$ is defined in [2]. For the levels of losses for which the blue line is drawn upper bisolitons exist for reduced dispersion $\bar{d}_0$ values between the ones given by the green and the blue lines. For the levels of losses for which blue line is not depicted we didn't find upper bisolitons. Lower bisolitons for a given level of losses exist for the reduced dispersion values $\bar{d}_0 \in [0, \bar{d}_0^{bif}]$

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