Energy Enhancement of Dispersion-Managed Solitons in Optical Fiber Transmission Systems with Lumped Amplifiers

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***Abstract*— We simulated dispersion-managed soliton propagation in optical fiber transmission systems with lumped amplifiers and loss. The energy enhancement of dispersion-managed solitons can be more or less than in the lossless case, depending delicately on the amplifiers arrangement. In all cases, there is a maximum enhancement factor beyond which the dispersion-managed soliton no longer exists and which also depends delicately on the arrangement.**

***Index Terms*— Dispersion-managed solitons, energy enhancement, fiber transmission systems.**

I. Introduction

DISPERSION-MANAGED soliton systems have attracted a considerable interest recently [1]–[5]. In these systems, the dispersion map has a low path-averaged dispersion value, so that the Gordon–Haus timing jitter is reduced improving the system performance [6]–[10]. Because of the large local dispersion in the map, dispersion-managed solitons have a larger energy relative to the energy of fundamental solitons in a uniform dispersion fiber with the same value of the average dispersion, resulting in an energy enhancement [3], [4], [11]. This work was all done neglecting loss in the optical fibers as is the case for almost all the theoretical work that has been done on dispersion-managed solitons to date. Of course the loss in real fibers is substantial, but it was shown a long time ago that standard solitons can be modeled using a lossless fiber if an approximately averaged soliton amplitude is used [12]. Thus, it was a bit surprising when Chin and Tang [13] showed recently that the enhancement factor is lower for a particular arrangement of lumped amplifiers located at the midpoints of the spans of the dispersion maps than it would be for a lossless fiber. However, this result did not clarify whether loss always lowers the enhancement factor. In the research reported in this letter, we examined several different amplifier arrangements, and we found in particular, that when the amplifiers are at the edges of the spans, then the enhancement factor increases relative to the lossless case. Moreover, we discovered in all cases that beyond some maximum value of the enhancement factor, the dispersion-managed soliton ceases to exist. However, this value depends strongly on the amplifier arrangement and the loss. Thus the behavior of the dispersion-managed soliton depends delicately on the amplifier arrangement and the loss. This result implies that while theoretical studies of dispersion-managed solitons in lossless fiber may yield useful qualitative insights, they are not quantitatively reliable.

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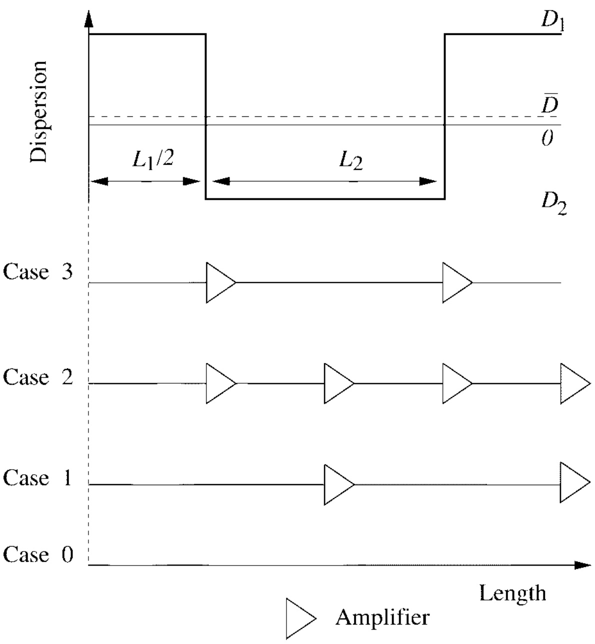

Fig. 1. Dispersion map and four different arrangements of the amplifier locations. The dispersion map consists of alternating anomalous and normal dispersion spans with lengths L_1 and L_2.

II. Simulation Results

Using three different arrangements of the lumped amplifier locations, we compared the energy enhancement factors of the dispersion-managed solitons to that of the lossless case. Fig. 1 shows schematically the dispersion map and three different arrangements of the amplifiers as well as the lossless case (Case 0). Case 1 shows an arrangement with the amplifiers at the point of maximum compression, corresponding to the case studied by Chin and Tang [13]. Case 2 shows an arrangement with the amplifiers at both the points of maximum expansion and compression. Finally, Case 3 shows an arrangement with the amplifiers at the point of maximum expansion. The

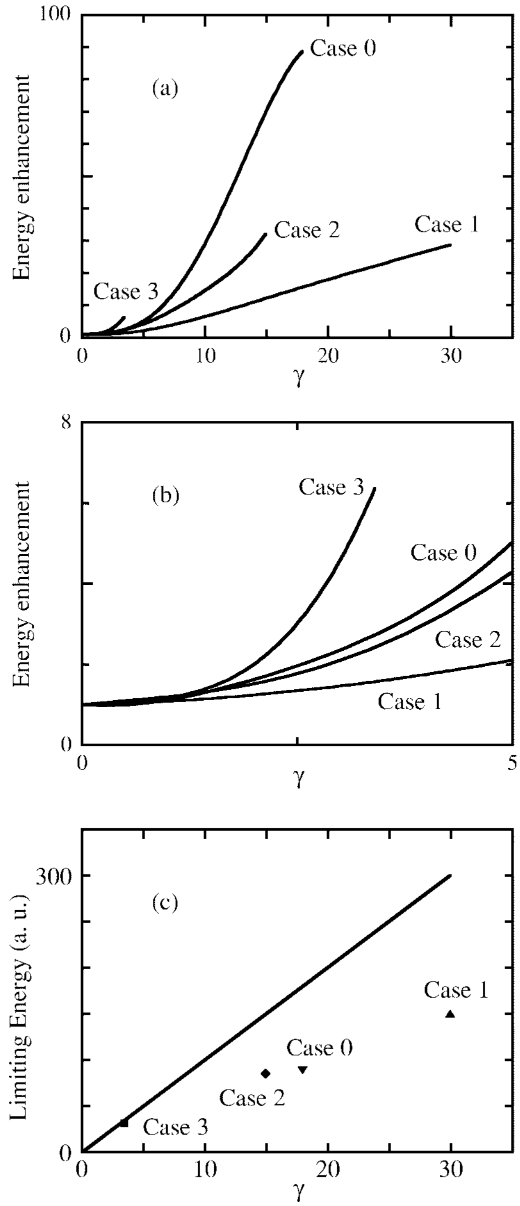

Fig. 2. (a) Energy enhancement factor for the four different cases. (b) Singularity points of enhancement factor exist for all four cases. (c) Comparison of the limiting energy of the dispersion-managed soliton at fixed pulsewidth (filled square, diamond, down triangle, and up triangle) in four cases with the the energy of the fundamental soliton with the same pulsewidth in local anomalous dispersion span (solid line).

dispersion D changes periodically with distance, alternating between positive (anomalous) dispersion D_1 with span length L_1 and negative (normal) dispersion D_2 with span length L_2, so that the path averaged dispersion $\overline{D} = (D_1 L_1 + D_2 L_2)/L_m$, where $L_m = L_1 + L_2$ is the map length, is anomalous. We chose a loss coefficient of 0.21 dB/km. Keeping $\overline{D}$, the FWHM pulse duration, and the loss coefficient constant while varying $\Delta D = (D_1 - D_2)$, we found the energy enhancement factors for the four different cases. In all our simulations, we chose $L_1 = L_2 = 100$ km and $\overline{D} = 0.0785$ ps/nm·km.

The energy enhancement factor is defined as the ratio of the averaged energy of the pulse to the energy of the fundamental soliton in a uniform dispersion fiber with the same average dispersion. The energy of the pulse is averaged over the whole span of the dispersion map. The dependence of the energy enhancement factor on $\gamma = 2[(D_1 - \overline{D})L_1 - (D_2 - \overline{D})L_2]/\tau_{\rm FWHM}^2$ is shown in Fig. 2(a) and (b) in each of the four cases. The different locations of the lumped amplifiers have a strong impact on the energy enhancement factor. The energy enhancement factor of Case 3 is the largest for a fixed value of γ, while the energy enhancement factor of Case 1 is the smallest. Physically, the reason is as follows: The local dispersion in each of the spans comprising the map is much larger than the path-average dispersion. The pulse behavior inside each span is dominated by linear dispersion, while a much weaker nonlinearity supports the pulse on average. When lumped amplifiers are located at the points where the pulse is most expanded, as in Case 3, the chirp of the pulse is at its maximum, thus resulting in a maximum energy enhancement factor. On the other hand, if lumped amplifiers are located at the points where the pulse is most compressed, the chirp of the pulse is nearly zero, resulting in a minimum energy enhancement factor, as indicated by Case 1.

In all four cases, we further discovered that as γ increases, there is a maximum value beyond which no solution exists. Hence, there is also a maximum value of the enhancement factor. The maximum values of γ and the enhancement factor correspond to the termination points of the curves in Fig. 2(a). If we attempt to inject pulses with more energy at larger values of γ, we find that the pulses continually radiate energy. At some values of γ, we also observe breathers. To understand this limit physically, we note that the dispersion-managed soliton ceases to exist when the nonlinear scale length becomes equal to the dispersive scale length in a single span to within a factor of two. The two scale lengths become comparable as γ grows because the local dispersion scale length is proportional to γ^{-1} while the nonlinear scale length is proportional to γ^{-2}. Dependence of the limit energy of the dispersion-managed soliton on γ is shown in Fig. 2(c). The solid line represents the energy of the fundamental soliton with the same pulsewidth in the anomalous dispersion span. As in the Case 3 the growth rate of the soliton energy is the fastest the soliton energy reaches its maximum value sooner than in the rest of the cases. It is intuitively clear that this maximum permissable energy is limited by the solid line.

It is desirable to reduce the Gordon–Haus timing jitter which depends inversely upon the energy enhancement factor. Thus, one might suppose that it is optimal to locate the amplifiers at the points of maximum expansion as shown in Case 3 in order to maximize the enhancement factor for a given value of γ. This result based on full numerical simulations is consistent with the results of [14] obtained using the variational approach. However, Fig. 2 also shows that significantly larger enhancement factors can be achieved with the arrangements in Cases 1 and 2. A practical limit on γ of about 3–4 exists due to the mutual interaction of solitons [4] and more work must be done to determine the optimal arrangement of the amplifiers—particularly in practical systems that often include filters as well. We tried several other amplifier arrangements too. The results suggest that when the least common multiple of the amplifier spacing and the map spacing is smaller than the dispersion length

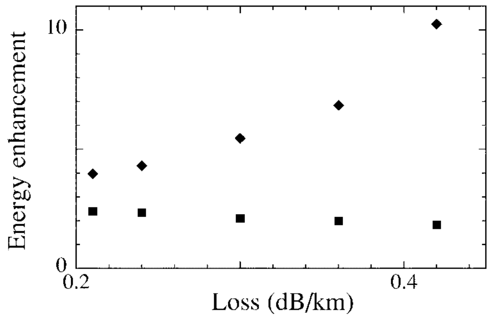

Fig. 3. The energy enhancement factor versus the fiber loss. Filled diamonds correspond to amplifier location Case 3, while filled squares correspond to amplifier location Case 1.

of the path-averaged dispersion, then stable pulses can be found. Otherwise, the pulse will continually shed radiation and disappear. Fig. 3 shows the dependence of the energy enhancement factor on the loss coefficient. In Case 1, the energy enhancement factor decreases with increasing loss, while by contrast in Case 3, the energy enhancement factor increases with increasing loss.

III. Conclusion

We numerically studied the energy enhancement of dispersion-managed solitons in an optical fiber with lumped amplifiers, and we showed that the energy enhancement factor depends delicately on the location of the lumped amplifiers in the optical fiber transmission line and the loss. The largest energy enhancement factors for a given value of γ occurs when amplifiers are located at the maximum expansion points. We found that when the amplifiers are located at the edges of the spans, the enhancement factor increases with increasing loss. Furthermore, we found that there is a singular value of γ in each case beyond which a dispersion-managed soliton no longer exists, and this value also depends delicately on the amplifier arrangement and the loss. These results indicate that in contrast to standard solitons, the dynamical behavior of dispersion-managed solitons cannot be accurately modeled in general using lossless fiber.

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