Study of Interactions of Co-propagative Solitons in an Optical Fiber

Etude des Interactions des Solitons Co-propagatives dans une Fibre Optique

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ABSTRACT

The originality of this work is to specify in detail the effect of each value of the phase on the solitonic interactions of both fundamental and higher order solitons as well as its use in the separation of adjacent solitons, and in suppressing interactions with different amplitudes. Firstly, we carry out a general study of the effect of the phase on two adjacent solitons in order to find the good value that is able to separate them during their propagation. Secondly, our study is focalized on the distinction of the two different cases of the interactions for repulsive and attractive cases according to the phase value. Then, we study the possibility of separating a group of solitons by injecting solitons with different amplitudes. Finally, the effect of the phase on the fission of the higher order solitons is analysed.

RESUME

L'originalité de ce travail est de préciser en détail l'effet de chaque valeur de la phase sur les interactions de deux types de solitons : les solitons fondamentaux et les solitons d'ordres supérieurs, ainsi que son usage dans la séparation des solitons adjacents, en plus de la suppression des interactions avec différentes amplitudes. Premièrement, nous réalisons une étude générale sur l'effet de la phase sur deux solitons adjacents dans le but de retrouver la bonne valeur qui permet leur séparation durant leur propagation. En second lieu, notre étude se focalise sur la distinction de deux différents cas d'interactions quand elle est attractive ou répulsive selon la phase. Ensuite, nous étudions la possibilité de séparer un groupe de solitons, en injectant des solitons avec différentes amplitudes. Finalement, nous analysons l'effet de la phase sur la fission des solitons d'ordres supérieurs.

1. INTRODUCTION

Solitons became of great importance in optical communication systems thanks to their robust nature. However, interaction of solitons is considered as bad effect. In this context, we use nonlinear Schrodinger equation resolved with Fast Fourier Transform to analyze the periodic solitons collisions in order to propose solutions to improve the propagation and avoid solitonic collisions. In optical communication systems, the bit rate is defined as the number of bits per second that can be transmitted along the optical fiber.Due to the waveguide and material dispersion of the optical fiber that broaden the pulses propagating the bit rate was shrink, and for a long time the dispersion was considered as major problem at high bit rates and for long haul optical communication systems [1].

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Until 1973 when Hasegawa and Tappert [2] proposed to offset the natural linear dispersion effect due to the group velocity dispersion (GVD) with the nonlinear effect called self-phase modulation (SPM) [3-5]. Subsequently in 1980, Mollenauer and his collaborators [6-11] realized experimentally the proposition and gave birth to stable waves called “solitons”. Since then they have been the subject of many extensive theoretical and experimental studies [12-15], especially for their applications in optical communication systems [16,17]. In counter to solitary waves that the collision would destroy their original identity, it was found in 1965 by Zabusky and Kruskal [18] that solitons are a special category of solitary waves because they behave like particles during the collision, by keeping their amplitude, shape, and velocity preserved. In soliton transmission, the necessity of carrying a massive information sending requires the propagation of multiple solitons at the same time in the so-called “soliton pulse train”. As a carrier of information, the soliton is surnamed a bit, and by definition, the more the bit rate is increased the better the communication is, but on the other hand the less is the time interval between two consecutive solitons the higher is the bit rate error [19]. Thus, the necessary temporal separation threshold is crossed and consequently harmful soliton interactions do appear. The Gordon Haus temporal jitter effect [20] has serious consequences on the optical soliton communication systems because it increases the bit rate error limiting significantly the potential of the communication system [11,13]. During the last decades, many research studies have been accomplished in order to minimize the effects of solitons interactions and improve the optical soliton communication systems [21-28]. The obvious solution consists in separating adjacent solitons by more than six times the temporal width of the pulse [29-45], but since exceeding the threshold is necessary, one cannot rely on time interval. In this paper, we give a special interest to soliton interactions. In addition, we study how they affect soliton collisions in order to minimize or eliminate the interactions. In the first part, we review the collision between solitons that can be either attractive or repulsive depending on the pertinent parameters that have a significant role during the interaction. In the best of our knowledge the role of the phase on solitonic interactions was considered in [44], but a detailed study of its effect on the attractions and repulsions was not done before.. For that, the simulation of the neighboring solitons is done as a function of different phases in order to show exactly its influence on the adjacent solitons and to specify when it induces attraction or repulsion. Furthermore, we study the influence of the temporal spacing, seen that this one plays an essential role in the attraction and the repulsion between solitons. Once the separation threshold is exceeded, the assembly/gathering of solitons starts to interact. The basic parameter on which is the intensity. Since the transmission requires many solitons sent together, suitable solutions to separate two solitons are not convenient to separate a set of solitons. The solution in this case is to inject solitons with different intensities. In [32], the authors proposed this solution, but they did not find a better separation as the one presented in this simulation. So, in the second study, we present the simulation results which prove that the propagation with different intensities is the best way to make the propagation free of collisions. To confirm the results, the simulation is made for 3 adjacent solitons, followed by 4 solitons and finally 5 solitons. In the third part, we study the effect of the phase on the fundamental solitons generated by the fission of the higher order solitons by the interaction. The physical interpretation of higher order soliton’s shape is that the amount of the positive chirp generated by SPM is greater than the negative chirp produced by GVD that is why it cannot be completely counterbalanced. Unlike robust fundamental solitons, higher order solitons are destructible in the presence of all kinds of perturbations: Hamiltonian (birefringence, dispersion) or non-Hamiltonian (attenuation, Raman effect, self-steepening) [38, 46-48]. The impressive phenomenon concerning the higher order soliton’s fission is the soliton-like disintegration whose number is the same as the order of the soliton, this means that a soliton of order N disintegrates into N pulses. This phenomenon is called “The decay of higher order solitons” [45-56]. The fission of the higher order solitons that exists in the literature is caused by the higher order effects described in the general Schrodinger equation ‘such as Raman Effect, self-steepening and higher order dispersion. However, there is an effect that causes fission of higher order

solitons not described in GNSE, it is through the interaction of higher order solitons [45-52]. The result of the fission of higher order solitons is disintegration to fundamental solitons. This distortion leads to a waste of information, but it can be useful in the generation of super continuums [45], or in the creation of ultrashort fundamental solitons at tunable frequencies. The reason why fission appears is because of attraction of electric field which depends on the time between the pulses and the relative phase difference of pulses.
In [39], the fission of spatial higher order solitons after collision is considered, but in our work we consider the fission of the temporal solitons, with the study of the influence of the phase on the fundamental solitons generated by the fission of higher order solitons, and here lies the particularity of this study.

Higher order solitons come apart (fission) when the optical loss is neglected, but in fact, losses in the fiber do always exist and should be taken into account. The attenuation makes them emerge so we get a fusion instead of the fission. This is the reason why we would like to finish this paper with a small review of the work present in [56] in order to show the difference between the fission and the fusion.

2. MATHEMATICAL MODEL

Starting from the higher-order nonlinear Schrödinger HNLS equation:

$$\frac{\partial A(Z,T)}{\partial Z} = +i\sum_{n=2}^{N}\frac{i^n}{n!}\beta_n\frac{\partial^n A}{\partial T^n} + \left(i\gamma(\omega_0) - \frac{i}{\omega_0}\frac{\partial}{\partial T}\right)\left[A(Z,T)\int_0^{\infty} R(T^{'})|A(Z,T-T^{'})|^2 dT^{'}\right] \quad (1)$$

where $\mathrm{i} = \sqrt{-1}$ and $\mathrm{A(Z,T)}$ is the slowly varying envelope of the optical soliton, $T = t_{lab} - \frac{Z}{v_g} \equiv t - \beta_1 Z$ is the temporal coordinate in retarded frame that moves at the group velocity v_g of the propagating pulse, Z is the spatial coordinate representing the distance of transmission, and β_n represents dispersion parameters of order n. For $n = 2$, β_2 is the second order GVD of second order and for $n = 3, \beta_3$ is the third order dispersion (TOD) parameter.
α is the attenuation factor. For standard silica fibers $\beta_2 \sim 20\, ps^2/km$ at $\lambda_0 \sim 1550\, nm$ [53]. $\gamma = n_2\omega_0/cA_{eff}$ is the nonlinear Kerr effect coefficient. n_2 is the nonlinear index coefficient, for silica fibers $n_2 = 2.2 \times 10^{-20}\, m^2/W$ at the same wave length [53]. The term proportional to $1/\omega_0$ governs the Kerr dispersion that is responsible of self-steepening and shock formation. The last term is responsible of self-frequency shift induced by intrapulse Raman scattering and T_R is related to the Raman response function. At wavelength $\lambda_0 \sim 1550\, nm$ T_R is approximately $3f_s$ [53]

For relatively broad pulses of width $T_0 > 5\, ps$, both steepening Kerr dispersion and self-frequency shift induced by Intrapulse Raman scattering become smaller about three orders of magnitude with respect to the other terms and can therefore be neglected. Furthermore, for pulses having a spectrum far from zero-dispersion wavelength the contribution of the third-order dispersion term can also be neglected and one can employ the simplified nonlinear Schrödinger equation NLS written below:

$$\frac{\partial A(Z,T)}{\partial Z} = -\frac{i}{2}\beta_2\frac{\partial^2 A}{\partial T^2} + i\gamma[|A|^2 A] \quad (2)$$

To solve NLS and HNLS equations we use the well-known split-step Fourier method [47] with a secant hyperbolic initial injected pulse:

$$A(z=0,T) = A_0\,\mathrm{sech}\left(\frac{T}{T_0}\right) \quad (3)$$

The simulation values used for our simulation are shown in the table 1.

Table 1.Simulation values

Parameter	values	Units
Non-linear parameter γ	1.0	1/W km
Dispersion of the second order β_2	-25	ps^2/km
Fiber Length L	10-80	km
Width of the impulse T_0	5.0	ps

The diagram used for the numerical simulation is shown in figure.1

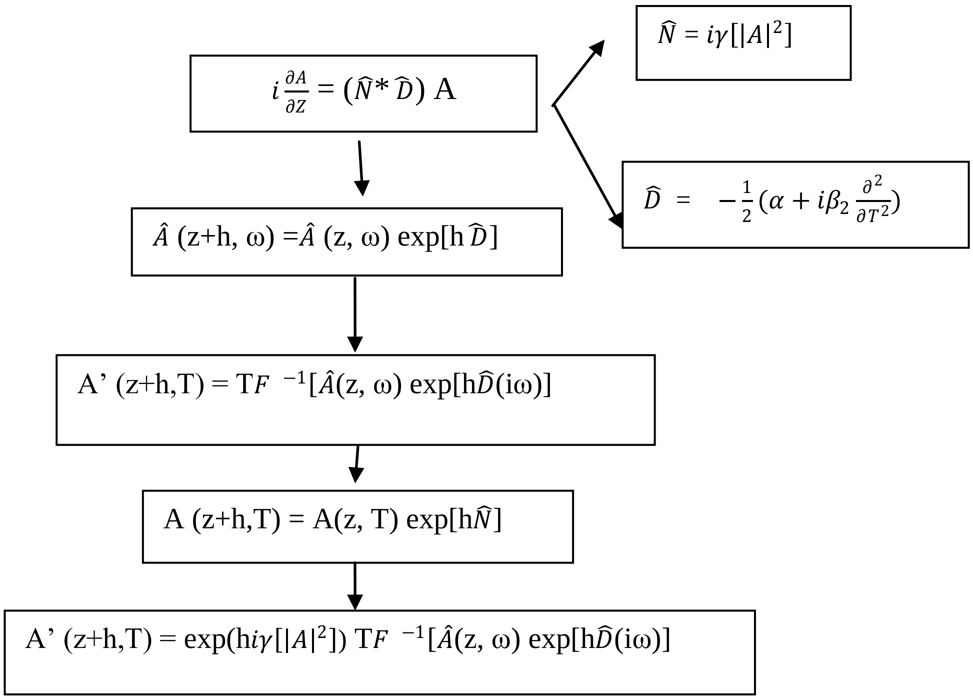


Figure 1. Flow chart of the simulation program

3. RESULTS

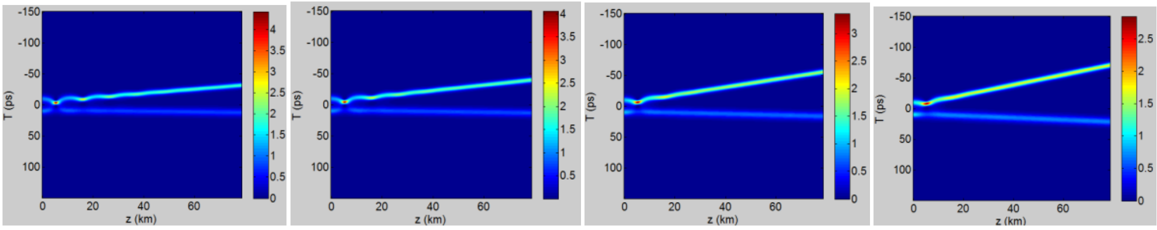
3.1. REPULSIVE AND ATTRACTIVE COLLISIONS

The equation used for this part is:

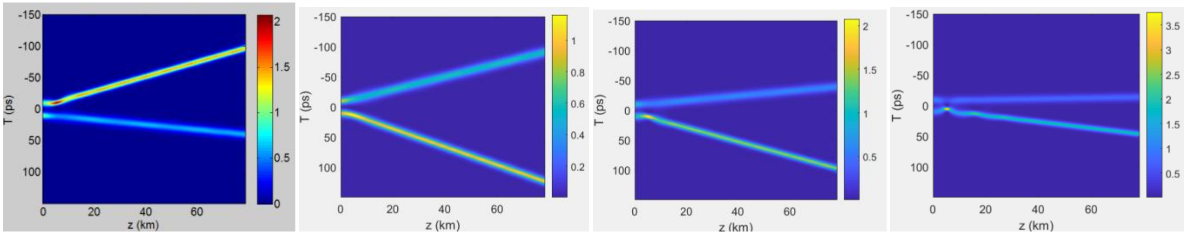
A = A_0*sech(t/(T_0- τ))*exp(i* θ_1)+A_0*sech(t/T_0+ τ)*exp(i*θ_2) .. (4)

A_0 : is the amplitude, θ: relative phase difference, τ= $\Delta t_0/T_0$ depends on the initial temporal separation Δt_0.

The repulsion of two solitons owning 0<θ_2<2π with $\theta_2 \neq 0$,$\theta_2 \neq$π and the constant time difference (τ = 2) are shown in the figure 2.



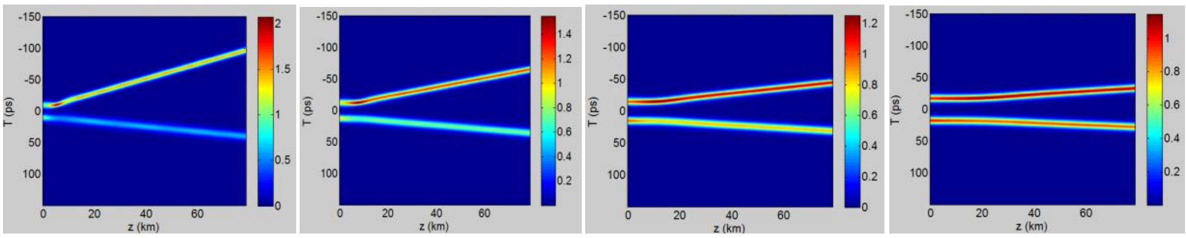
$\theta_2 = \pi/8$ $\theta_2 = \pi/6$ $\theta_2 = \pi/4$ $\theta_2 = \pi/3$



$\theta_2 = \pi/2$ $\theta_2 = 1.2\pi$ $\theta_2 = 1.5\pi$ $\theta_2 = 1.8\pi$

Figure 2. Repulsion between two solitons for τ = 2 (θ_1=0 order θ_1; $\theta_2$different values of θ_2)

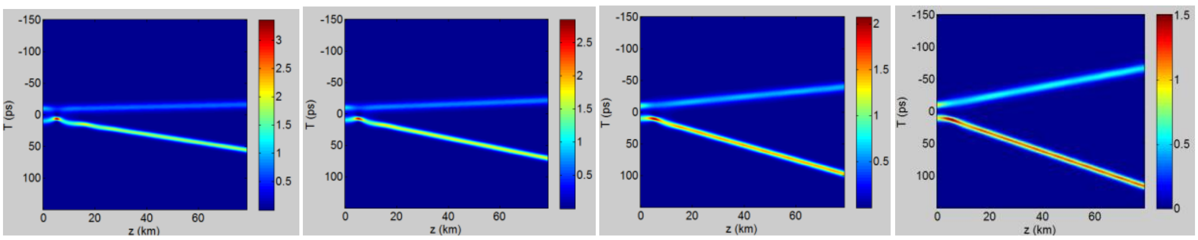
The repulsion of two solitons with $\underline{\theta_1}$=0, $\underline{\theta_2}$= π/2 and the different time difference τ = 2.2.5, 3, and 3.5 respectively are presented in figure.3.



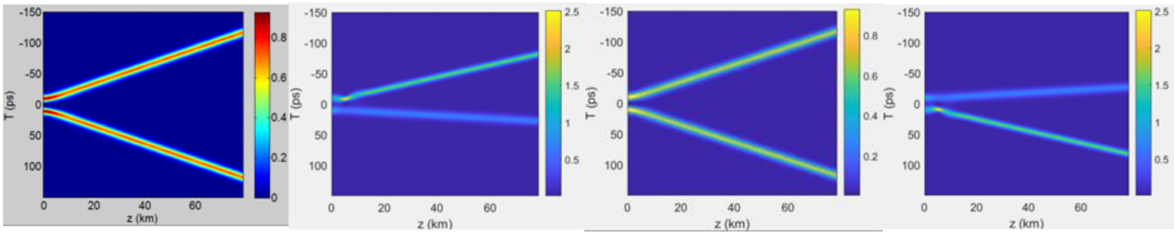
τ =2 τ=2.5 τ=3 τ=3.5

Figure 3. Repulsion with transfer of energy between two solitons for different temporal separations (θ_1=0; θ_2=π/2)

The repulsion of two solitons with opposite phases and τ=2 are shown in figure 4.



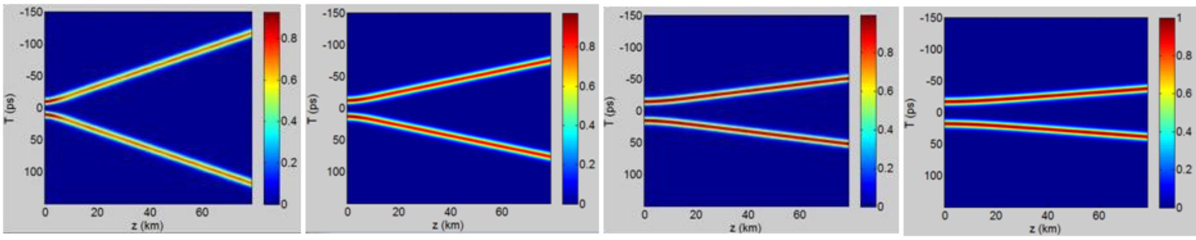
$\theta_{1,2} = \pm\, \pi/8$ $\theta_{1,2} = \pm\, \pi/6$ $\theta_{1,2} = \pm\, \pi/4$ $\theta_{1,2} = \pm \pi/3$



$\theta_{1,2} = \pm\pi/2$ $\theta_{1,2} \pm 1.2\pi$ $\theta_{1,2}=\pm\frac{3\pi}{2}$ $\theta_{1,2} = \pm 1.8\pi$

Figure 4. Repulsion of two solitons with opposite phases and τ=2

The repulsion of two solitons with $\underline{\theta_{1,2}}=\underline{\pm}\pi/2$ and different value of τ = 2, 2.5, 3, 3.5 are shown in figure 5.



τ =2 τ=2.5 τ=3 τ=3.5

Figure 5.Repulsion with identical intensity between two solitons for different values of τ (θ_1=-π/2 and θ_2= π/2)

An impressive result is obtained from equation 5, such as θ_1=-π and θ_2= π, instead of obtaining a repulsion, an attraction takes place as shown in figure.6.

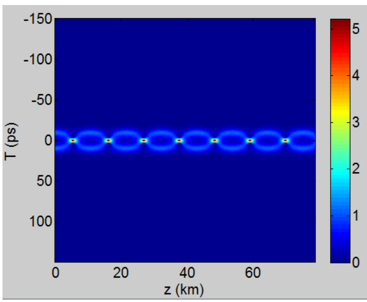
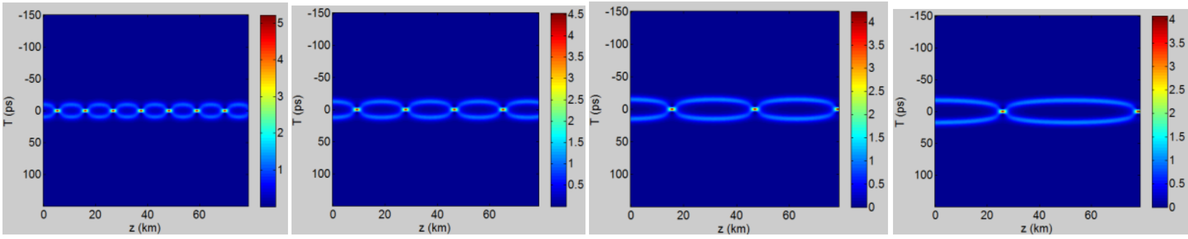


Figure 6. Attraction between solitons with opposite phases (π and –π)

In figure7, we show how the temporal separation affects the periodicity of attraction is shown.



τ=2 τ=2.5 τ=3 τ=3.5

Figure 7. Attraction between two solitons for different values of τ

3.2. INFLUENCE OF PHASE AND INTENSITY ON COLLISIONS

The following equations (5-7) are used:

$$A= A_1\text{sech}\,[A_1(t/T_0 - \tau)]*\exp(i\theta_1) + A_2\text{sech}\,[A_2(t/T_0)]*\exp(i\theta_2) + A_3\text{sech}\,[A_3(t/T_0 + \tau)]*\exp(i\theta_3) \quad (5)$$

$$A= A_1\text{sech}\,[A_1(t/T_0 - 2\tau)]*\exp(i\theta_1) + A_2\text{sech}\,[A_2(t/T_0 - \tau)]*\exp(i\theta_2) + A_3\text{sech}\,[A_3(t/T_0 + \tau)]*\exp(i\theta_3) + A_4\text{sech}\,[A_4(t/T_0 + 2\tau)]*\exp(i\theta_4) \quad (6)$$

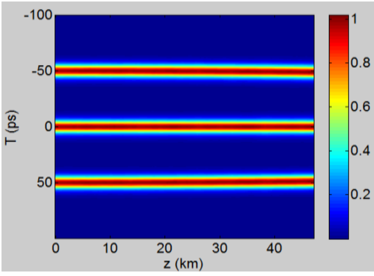
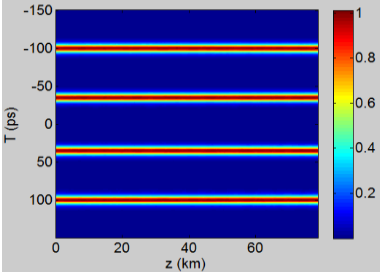
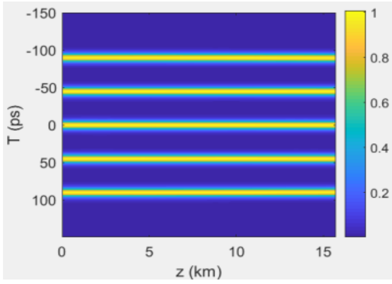
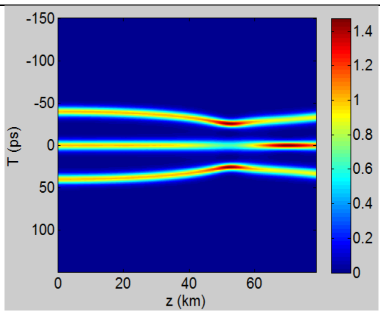
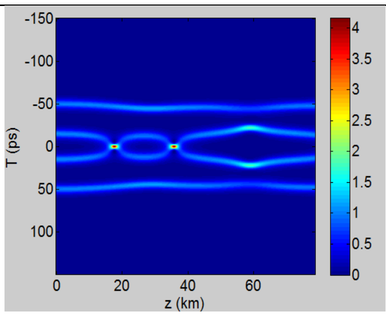
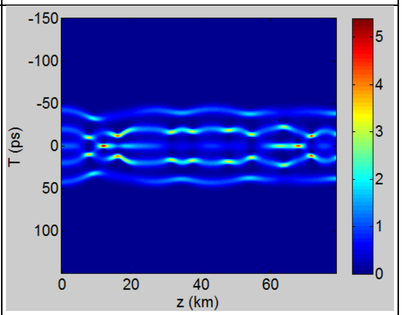
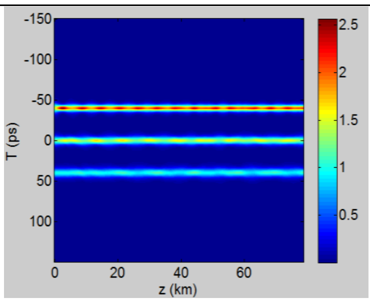
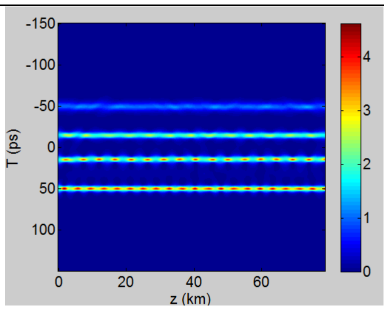
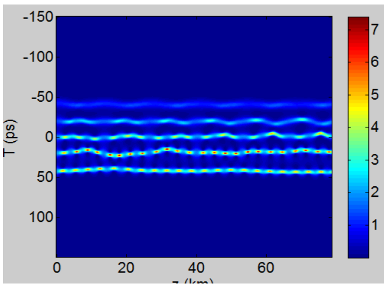
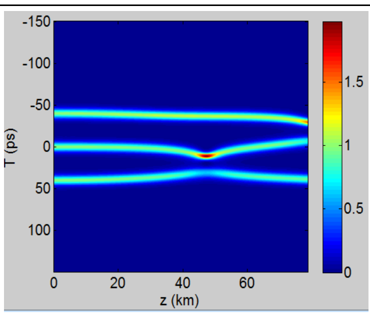
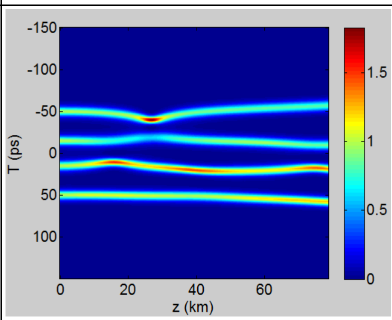
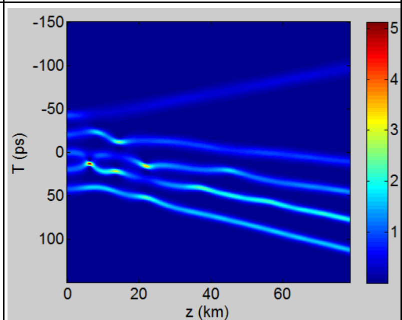
$$A= A_1\text{sech}\,[A_1(t/T_0 - 2\tau)]*\exp(i\theta_1) + A_2\text{sech}\,[A_2(t/T_0 - \tau)]*\exp(i\theta_2) + A_3\text{sech}\,[A_3(t/T_0)]*\exp(i\theta_3) + A_4\text{sech}\,[A_4(t/T_0 + \tau)]*\exp(i\theta_4) + A_5\text{sech}\,[A_5(t/T_0 + 2\tau)]*\exp(i\theta_5) \quad (7)$$

The values used in the simulation are:

- Phases: $\theta_i = \pi/2, \pi/3, \pi/4, \pi/6, \pi, 1.2\pi, 1.5\pi, 1.8\pi, 2\pi$,
- Intensities: $A_0 = 1.0W$, $A_1 = 1.2W$, $A_2 = 1.5W$, $A_3 = 1.7W$, $A_4 = 2.0W$, $A_5 = 2.3W$

The table.4 gathers the figures (8-19) that present the propagation of a group of solitons separated using different intensities and different phases.

Table.4. Separation of solitons using phase and amplitude and the phase

Number of solitons	X=3	X=4	X=5
an important temporal separation			
X identical solitons: with the same intensities and phases			
X different solitons of equal intensities and phases			
X solitons with same intensities and different phases			

3.3.1. FISSION OF HIGHER ORDER SOLITONS BY INTERACTIONS

We would like to compare the fission of the higher order solitons in-phase and out-phase to specify its effect, for this reason we chose to couple each soliton of the same order. The equations used for simulation are respectively:

For solitons with opposite phase:

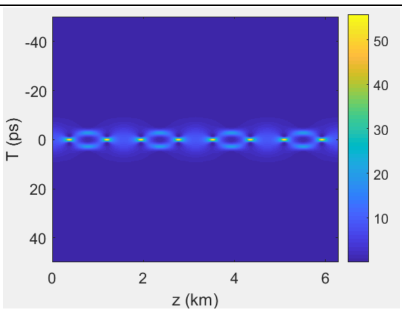
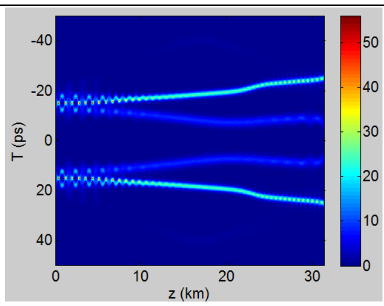
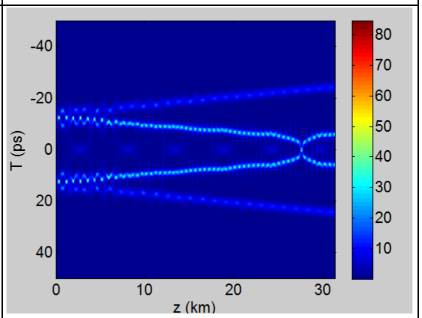
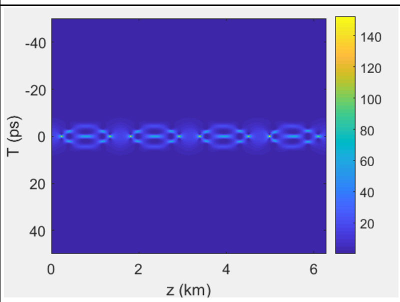
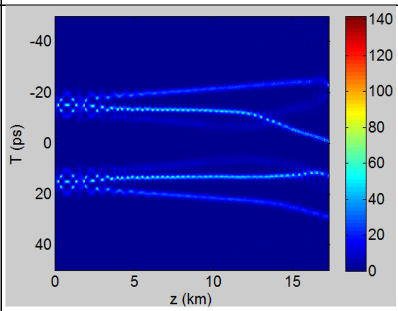
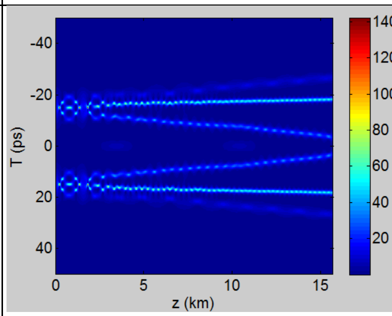
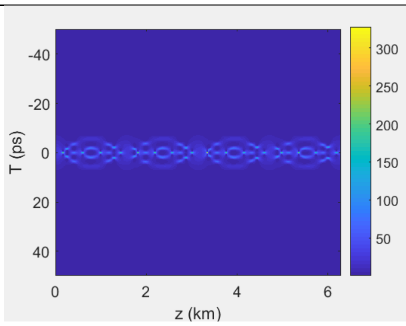
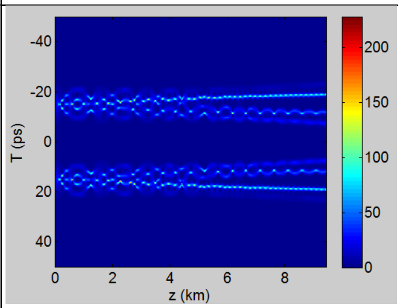
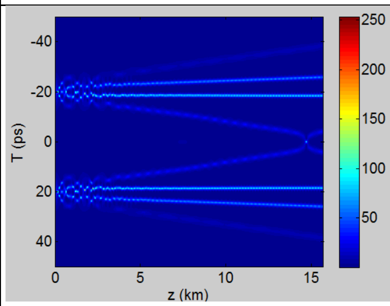
$$A = A_i^2 *\text{sech}\,(t/T_0-3) *\exp(i*\pi/2\ )+ A_i^2 *\text{sech}(t/T_0+3)*\exp(-i*\pi/2\ ) \tag{8}$$

For solitons without phase :

$$A = A_i^2 *\text{sech}(t/T_0-3) +A_i^2 *\text{sech}(t/T_0+3) \tag{9}$$

The values of the simulation are shown in table 5 that groups figures (20-28), The process of the fission of two solitons of higher order is illustrated in figure.29:

Table 5. Fission of solitons by interaction

Order	Propagation of one higher order solitons	Propagation of two higher order solitons with opposite phase	Propagation of two higher order solitons with same phase
3rd			
4th			
5th			

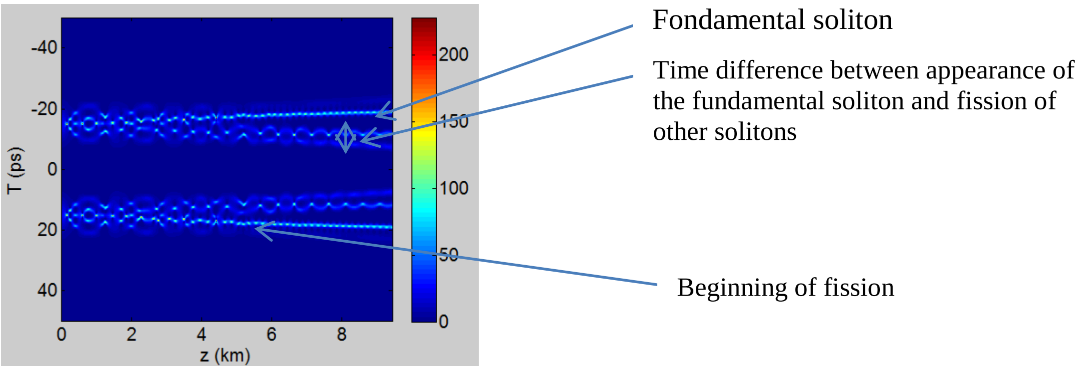
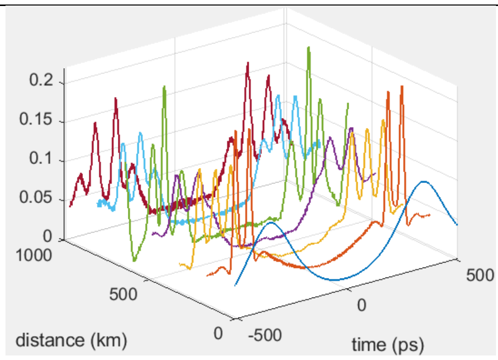
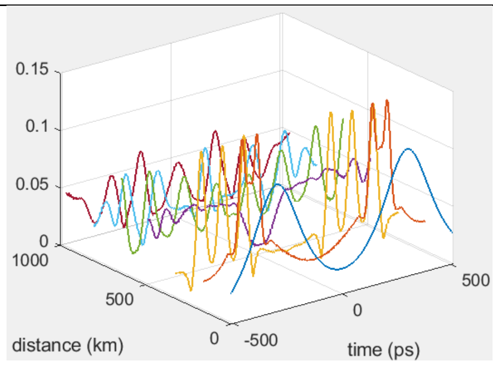
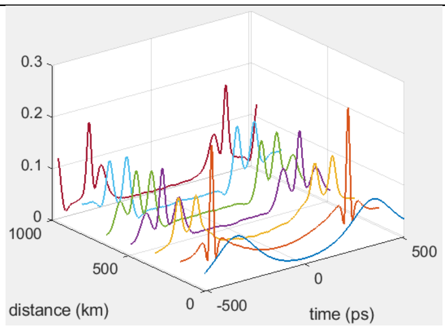
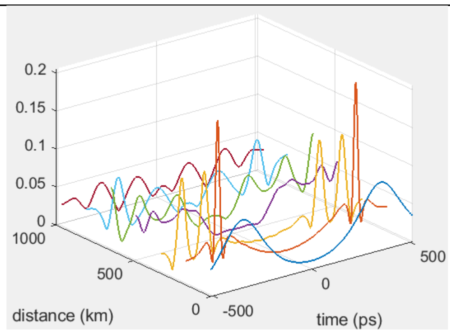
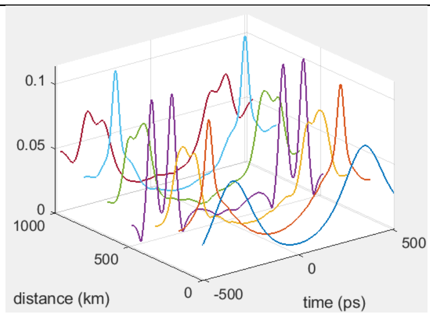
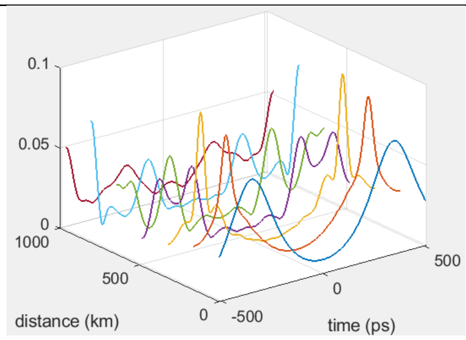


Figure 29 Fission of higher order solitons

3.3.2 FUSION OF HIGHER ORDER SOLITONS

Table 6 : Solitons with and without fiber loss

Solitons order	without attenuation	attenuation on adjacent solitons
5^{th}		
4^{th}		
3^{rd}		

4. DISCUSSION

In this section, the propagation of higher order solitons whith and without fiber loss are studied. The cases considered are for the propagation of 5th , 4th and 3rd order solitons with attenuation on adjacent solitons and /or with attenuation at all. The results are summerized in Table 6

4.1. Attraction and repulsion

- It is noticed that there is not only repulsion between solitons in all cases ($\theta_1 = 0$ and $0<\theta_2<2\pi$) (figures 2 and 3), but also an exchange of energy which appears as a variation of intensity. The identical initial intensity changes after a considerable propagation because of the energy transfer from the leading to the trailing pulse when $\theta_2< \pi / 2$ and from the trailing to the leading when $\theta_2> \pi / 2$, noting that the quantity of energy transferred is a function of the phase. It is proportional to the phase if $\theta_2< \pi / 2$ and inversely proportional to the phase if $\theta_2> \pi / 2$. The strength of repulsion is also function of the phase in the same way. When $\theta_2< \pi / 2$, the greater the phase θ_2 the greater is the repulsion, noting that the trailing pulse makes a higher temporal shift than the leading pulse. When $\theta_2> \pi / 2$, the greater the phase θ_2 the smaller is the repulsion, and contrary to the last case, the shift of the leading pulse is higher than the trailing one. For all values of θ_2 when $\theta_1= 0$, there is an attraction between two pulses before the repulsion. The impact of the initial temporal separation between two pulses is illustrated in the Figure 3. From the figure above, shows that the repulsion is inversely proportional to temporal separation τ and the larger the separation is, the smaller the repulsion is. The less important energy transfer more the separation increases.

In figure5 solitons having opposite phases ($\theta_1 = -\theta_2$) undergo an attraction before the repulsion except for two cases ($\theta_1= \pi/2$ and $\theta_2 = -\pi/2$) or ($\theta_1= 3\pi/2$ and $\theta_2 = -3\pi/2$). However when the two opposite phases are equal to ($\theta_1= \pi/2$ and $\theta_2 = -\pi/2$) or ($\theta_1= 3\pi/2$ and $\theta_2 = -3\pi/2$) , they undergo a direct and symmetric repulsion, without any energy exchange between them because the amplitudes remain equal for two solitons, noting that the temporal shift is the same for both pulses. Otherwise, for other phase values, the repulsion is assymmetric. The leading pulse gets shifted more than the trailing pulse if ($\theta_1 < \pi/2$ and $\theta_2 < -\pi/2$) and ($\theta_1 >3\pi/2$ and $\theta_2 > -3\pi/2$) . For this interval, the energy is transfered from the trailing to the leading pulse. If ($\pi/2< \theta_1 < 3\pi/2$ and $-\pi/2> \theta_2 > \underline{-3\pi/2}$) , the shift of the trailing pulse is higher than the leading pulse. The transfered energy is from the leading to the trailing pulse in the interval ($\pi/2< \theta_1 < 3\pi/2$ and $-\pi/2> \theta_2 > -3\pi/2$) .
The impact of the bit rateτ on the propagation of pulses with opposite is shown in the figure 5 with the chosen phases ($\theta_1 < \pi/2$ and $\theta_2 < -\pi/2$) . In this case the repulsion is inversely proportional to temporal separation τ. In the case where two opposed phases are considered ($\theta_1= \pi$ et $\theta_2= -\pi$) or are both null, one obtains a periodic attraction is obtained. The scenario of attraction illustrated in the Figure.6, shows that it is symmetric and occurs without any shift or energy exchange for two solitons. The temporal separation τhas an impact on the periodicity of the attraction as shown in the figure 7. It is found that the period is proportional to the spacing time because it increases with the increase of the bit rate τ.

4.2. PHASE AND INTENSITY EFFECTS

Simulation results, indicates that distant solitons remain perfect during propagation. In the following, the whole simulation is carried out with solitons close enough to create Kerr-induced interaction, ie, we have exceeded the threshold separation to study the possibility of separating them using different amplitudes and different phases. When up to three solitons propagate together in the same optical fiber with the same phases and amplitudes, as present the figures (9, 13, 17), we note that the solitons then repulse and attract at certain points. It is noticed from the second column of the Table.4 the symmetry of collisions occurs with the same scenario at left and right side.
In addition the symmetry of energy transfer takes place between neighboring solitons at both right and left sides. The effect is related to Kerr nonlinearity, which precisely intrapulse FWM.

The variation of the amplitude of the co-propagating solitons gives a perfect separation and stability of co-propagating solitons, It retains the initial characteristics of the solitons unless there is some variation of intensities that indicates the energy transfer from soliton with higher intensity to the others due to intrapulse FWM.
Finally , when the same amplitude is maintained and we change the phase of the neighboring solitons. The result is an asymmetric entanglement between the solitons, an asymmetric energy exchange, and an unequal temporal shift of solitons. Its explained by the difference in the phases which causes a variation in travelling speed of the pulses, changing the symmetric interaction behavior induced by Kerr non-linearity.

There fore the difference of amplitudes is remains the best choice to improve the propagation of a set of solitons and to avoid collisions.

4.3. FISSION BY INTERACTION

The fission of higher order solitons caused by interaction occurs by the approximation of two solitons. This induces a disturbance exchanged mutually by two solitons that disintegrate after a distance L_S [55] defined as the fission distance:

$$L_S = \sqrt{\frac{\tau_0}{|\beta_2 \gamma P_0|}} \qquad (10\ a)$$

$$L_S = \frac{L_D}{N} \qquad (10\ b)$$

The intensity of fundamental generated solitons is:

$$P_j = P_0(2N - 2j - 1)^2 \qquad (11)$$

Where N is the order of solitons, j is the number of the fumdamental generated soliton.

For example, if one takes the soliton of order 4, the first fundamental soliton has an intensity 3.06 times more than that of the original soliton of order 4, the second is higher by 1.56, the third by 0,56 times, and the last 0.06 times. The fission of solitons of order N gives rise to N-1 fundamental soliton if (3 <N <8) and N-2 if (9 <N <15), in this work, order up to 5.are considered.

The pattern of higher order solitons is illustrated in the figures (20, 23, 26). The simulation is based on equation 12

$$A = N_i^2 * \mathrm{sech}(t/T_0) \qquad (12)$$

The values used for simulation are presented in the Table 5 : $N_2 = 2, N_3 = 3,\ N_4 = 4, N_5 = 5$.

The results confirm that solitons fission is possible by interaction and N-1 fundamental solitons appeared. By comparing the figures, it is noted that the phase has an effect on fundamental generated solitons. In case of opposite phase, fundamental soliton's shape remains straight, whereas in case of the same phase, generated solitons deviate witnessing bends.

On the other hand, if phases are opposite, fundamental solitons do not appear at the same time as for those in phase. This is very clear for the solitons of order 5 as illustrated. The fission length depends on the order of the solitons, as for example the soliton of order 5 to disintegrate after a single period, while the solitons of order 4 took 2 periods. After fission, N-1 fundamental solitons appear.

Table (30-35) show that despite the shape preserving propriety of soliton pulses due to exact compensation of non-linearity and dispersion, it may be broadened because of the loss of the optical fiber. In this case, if two solitons of higher order co-propagate, fiber loss will cause fusion instead of fission because it increases the interaction.

5. CONCLUSION

One of the advantages of solitons is their invariance in the case of interaction. However, it is sought to transmit solitons without interaction during propagation. Therefore, it is interesting to find how to separate them and at the same time, transmit as much information as possible. In this paper the interaction of co-propagative solitons has been studied. Simulation results show that fundamental solitons undergo a collision that may result in an attraction or repulsion according to the values of the phase. The attraction appears when two solitons are of opposite phases (π and -π) or both null, otherwise with the exception of these cases there is repulsion of solitons. These collisions induce a time shift as well as a variation of the intensity, which varies according to the value of the phase. If the number of adjacent solitons exceeds two, the solution to separate them is to choose unequal intensities.

The interaction of higher order solitons leads to their fission into fundamental solitons when there is no attenuation in the fiber. Two cases are distinguished. In-phase colliding solitons propagate in a straight line while opposite-phases ones propagates in a twisted form. If the optical fiber has a high attenuation, collision of higher order solitons leads to their fusion and destruction.

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