Efficient control of the energy exchange due to the Manakov vector-soliton collision

R. Radhakrishnan,* Patrice Tchofo Dinda, and Guy Millot
Laboratoire de Physique de l' Université de Bourgogne, UMR CNRS No. 5027, Avenue A. Savary, Boîte Postale 47 870, 21708 Dijon cédex, France
(Received 15 September 2003; published 28 April 2004)

By examining the concept of energy exchange among the orthogonally polarized components of each of two colliding (Manakov-like) vector solitons it is observed that a maximum or an efficient energy-exchange process is possible only for an appropriate choice of the initial physical parameters (namely, frequency separation, polarizations, time delay, and pulse-width separation between the colliding solitons) for which L_W (walk-off length) $\gg L_{NL}$ (nonlinear length). However, in this case only, the amount of energy-exchange can be considerably increased or decreased by appropriately changing the phases of colliding solitons without altering the walk-off length and the initial energy distributions between the soliton components. Moreover we observe that during the collision between two closely placed vector solitons of the practically interesting integrable Manakov model, nonuniform pulse broadening takes place in each of their components. Such an effect has not yet been reported in any $(1+1)$ dimensional integrable soliton systems so far. In addition, the relation between walk-off length, polarization, and pulse width is briefly discussed.

DOI: 10.1103/PhysRevE.69.046607 PACS number(s): 42.81.Dp, 42.65.Tg, 41.20.Jb

I. INTRODUCTION

Zakharov and Shabat [1] developed the inverse scattering theory (IST) to integrate the nonlinear Schrödinger (NLS) equation which appeared later as a mathematical model to govern the dynamics of optical scalar solitons in an ideal single-mode fiber [2,3]. But in reality, the simplest model is a two-component pulse in a waveguide that supports pulses along two orthogonal polarizations as a result of birefringence effects. Therefore by coupling two NLS equations through cubic nonlinearities, the two-component vector-soliton system was first suggested and solved using the IST by Manakov [4]. The extension of this study to the general integrable *N*-component case is straightforward [5]. Such coupled equations having a coupling term that is function of the sum of the all field intensities were systematically derived in nonlinear optics field [6–16] to explain certain concepts as pointed out below.

Recently the Manakov vector-soliton received renewed attraction because it was observed experimentally in single-mode fiber [6], planar waveguide [7], and photorefractives [8]. However, theoretically, vector soliton was realized more than a decade ago in the single-mode fiber through the self-trapping phenomenon as reviewed in Ref. [9]. In addition, very recently ideal Manakov spatial solitons in quadratic media was observed via cascading optical rectification and the electro-optic effect [10].

One of the most exciting phenomena associated with the vector-solitons is their collision. Manakov carried out one of the pioneering studies [4] on the collisions between vector-soliton pulses asymptotically in different polarization states and obtained an exact expression for the change in polarization state of the colliding pulses. Later on it was shown that the pulse evolution in optical fibers with randomly and rapidly varying birefringence can be described by the Manakov equation [11]. Further Menyuk [12] derived the Manakov equation to govern pulse propagation when the value of the ellipticity angle of the birefringent fiber is 35 °. In this case he also claimed that a soliton of one polarization, when interacting with a switching pulse of the other polarization, does not develop shadow or daughter wave (transfer of energy from one polarization axis to the other due to collision). But Radhakrishnan *et al.* [13] proved by studying the vector-soliton collision through the general two-soliton solution of the Manakov model that there is an energy exchange between the polarization components of each colliding vector soliton. Based on this study, Jakubowski, Steiglitz, and Squier, and later Steiglitz, mentioned in Ref. [14] that such types of collisions besides being fundamentally interesting have also opened the exciting possibility of soliton applications to the implementation of all-optical logic in a way that does not require fabrication of individual gates [14]. Further Anastassiou *et al.* [15] observed such strong energy-exchange collisions experimentally. In addition, recent results [16] have demonstrated the possibility of using vector-solitons in Bose-Einstein condensates media to perform quantum information processing. Moreover the studies of polarization changes due to collision between the vector-solitons of Manakov model [13–18] have important consequences in soliton transmission systems that use polarization division multiplexing (PDM) [19,20]. In a PDM system, adjacent solitons are launched along orthogonal polarizations. This technique can double the transmission rate as shown in Ref. [16], experimentally. By analyzing orthogonal-soliton interactions in the Manakov system, the benefit of the PDM technique was analytically demonstrated in Ref. [17].

Therefore by considering the importance of vector-soliton collisions supported by the Manakov model in different aspects, in this paper, we like to investigate how the efficiency of energy-exchange processes varies with respect to initial parameters such as frequency, polarization, pulse width,

*Permanent address: Department of Physics, Jamal Mohamed College, Trichy 620 020, India. Electronic address: rrk68@yahoo.com

phase and time delay of the colliding vector-solitons in Secs. II and III. Indeed, in the earlier studies, Manakov [4] noted that the polarization changes during vector-soliton collisions and Radhakrishnan *et al.* [13] observed an energy-exchange between the polarization components of each vector solitons, provided that the unit polarization vectors of the colliding solitons are neither parallel nor orthogonal. The main objective of the present study is to determine under what conditions the maximum amount of energy is transferred from one component to the other. The obtained condition exhibits the interesting relation between the polarization and walk-off length.

II. MANAKOV EQUATION

Manakov equation can be written as

$$i\frac{\partial u_m}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 u_m}{\partial^2 t} + \gamma(|u_m|^2 + |u_{3-m}|^2)u_m = 0, m = 1,2, \quad (1)$$

where $u_1(z,t)$ and $u_2(z,t)$ are the two orthogonally polarized components of the slowly varying envelope pulse $\mathbf{u} = (u_1, u_2)^T$, z and t are, respectively, the distance and time, β_2 is the group-velocity dispersion parameter, and γ is the fiber nonlinearity. Throughout the present paper, to make the presentation clear, the time is expressed in units of picoseconds (ps), the distance in kilometers (km), and the amplitudes of the soliton components u_1 and u_2 in $\sqrt{\text{Watt}}$.

In order to investigate the vector-soliton collision, we want to consider the sum of two different vector one solitons S_1 and S_2 supported by the Manakov model, namely, at $z = 0$ as

$$\mathbf{u}^{(S_j)} = \mathbf{C}^{(S_j)}\sqrt{P_0^{(S_j)}}\exp(i\eta_I^{(S_j)})\text{sech}(\eta_R^{(S_j)}), j = 1,2, \quad (2)$$

where $\eta_R^{(S_j)} = A^{(j)}(t + t_0^{(j)})$, $\eta_I^{(S_j)} = \omega^{(j)}t + \eta_0^{(j)}$, and $\mathbf{C}^{(S_j)} = [\cos(\theta^{(j)})\exp(i\phi_1^{(j)}) \quad \sin(\theta^{(j)})\exp(i\phi_2^{(j)})]^T$ is the Jones vector, in which the superfix j represents vector soliton S_j while suffixes 1 and 2 define components u_1 and u_2 of the vector soliton S_j, $P_0^{(S_j)}$ is the initial peak power of soliton S_j, $\delta_0^{(j)} = 1/A^{(j)}$ is the half-width at $1.145/e$ of the peak power of soliton S_j components, $\triangle t = t_0^{(2)} - t_0^{(1)}$ is the initial time delay or the central position difference between the two solitons, $\Delta f = (\omega^{(2)} - \omega^{(1)})/2\pi$ is the initial frequency separation between the solitons. The Jones vector $\mathbf{C}^{(S_j)}$ contains all the informations about the polarization state of the soliton S_j, where $\theta^{(j)}$ is the azimuthal angle, $\phi_2^{(j)} - \phi_1^{(j)}$ is the initial phase difference between the two components of soliton S_j, and $\eta_0^{(j)}$ is the arbitrary in-phase constant of soliton S_j. Manakov [4] noted asymptotically that during vector-soliton collision, except the position shift all other physical parameters (namely, pulse-width, velocity, polarization, and frequency) are not affected provided their initial polarizations are parallel ($\mathbf{C}^{(1)} \parallel \mathbf{C}^{(2)}$, i.e., $\theta^{(1)} = \theta^{(2)}$ and $|\phi_2^{(j)} - \phi_1^{(j)}| = 0$ or π) or orthogonal ($\mathbf{C}^{(1)} \perp \mathbf{C}^{(2)}$, i.e., $|\theta^{(2)} - \theta^{(1)}| = \pi/2$). Otherwise in addition to the position shift, the associated Jones vectors $\mathbf{C}^{(S_j)}$ do change without disturbing other parameters. Here the value of position shift depends on their initial polarizations [13,21].

III. NUMERICAL RESULTS AND DISCUSSIONS

The Manakov equation (1) is a nonlinear partial differential equation that does not generally admit analytic solutions except for some specific cases such as those mentioned in Sec. II. For all other cases, numerical solution of Eq. (1) is therefore needed to obtain the dynamical behavior of the vector soliton. Throughout the present work we have solved Eq. (1) by means of the split-step Fourier method [9]. Whereas dispersion and nonlinearity act together along the fiber, the split-step Fourier method assumes an approximate (but highly accurate) solution, in which propagation from z to $z + dz$ is carried out in two steps. In the first step, the nonlinearity acts alone whereas in the second step the dispersion acts alone. Mathematically, the evolution of the soliton field, say u_j, is given by

$$u_j(z + dz, t) = \exp(dz\widetilde{D})\exp(dz\widetilde{N})u_j(z,t),$$

where $\widetilde{D}$ and $\widetilde{N}$ are differential operators that correspond to dispersion and nonlinearity effects, respectively. For sufficiently small dz, this method leads to a highly accurate solution for almost all standard pulse-propagation equations.

A. Influence of the initial frequency separation

We will first see below how the process of energy-exchange among the components of each colliding vector-soliton (as noted by deriving the most general two-soliton solution of Eq. (1) in Ref. [13]) is affected with respect to the initial frequency separation Δf. For this purpose we select the two vector one-solitons of the form (2) having equal pulse width value of 5 ps and equal peak power of 0.2 W. By restricting the azimuthal angle of the two solitons to the value of 45°, the power is equally distributed in each component of the colliding solitons S_1 and S_2. But the initial phase difference for soliton S_1 is 0 and π (i.e., here $\phi_2^{(1)} = \phi_1^{(1)} = \phi_1^{(2)} = 0$ and $\phi_2^{(2)}$ is other than 0 and π). Through this choice we select the initial Jones vectors $\mathbf{C}^{(1)}$ and $\mathbf{C}^{(2)}$ of the colliding solitons to be neither parallel nor orthogonal so that the energy exchange is possible due to the collision. Here we take $\beta_2 = -20\ \text{ps}^2\ \text{km}^{-1}$, and the value of $\gamma = 4\ \text{W}^{-1}\text{km}^{-1}$ follows from the condition of soliton period [9]. Further, through this study the initial time-delay (Δt) or the central position difference between S_1 and S_2 is 56 ps. This is achieved, for example, by placing S_1 at $t = 28$ ps and S_2 at $t = -28$ ps. With such temporal positions, the dynamics of S_1 and S_2 before and after collision appears equally on the both side of $t = 0$, as shown in Fig. 4. Therefore during the numerical simulation, the powers and energies of S_1 and S_2 (components wise) can be calculated exactly outside the collision region, by separating S_1 and S_2 with respect to $t = 0$ at different z. Such symmetric timefiller proposed for this study is needed because our Δf range introduces spectral overlap as explained below. In addition, it is worth noting that depending on the precollision parameters the collision of two vector solitons of the form (2) may be attractive or repulsive, and/or, elastic or inelastic [13]. So, after a given collision, irrespective of the precise nature of the collision, we hereafter simply designate the component of soliton S_1 (S_2) which has

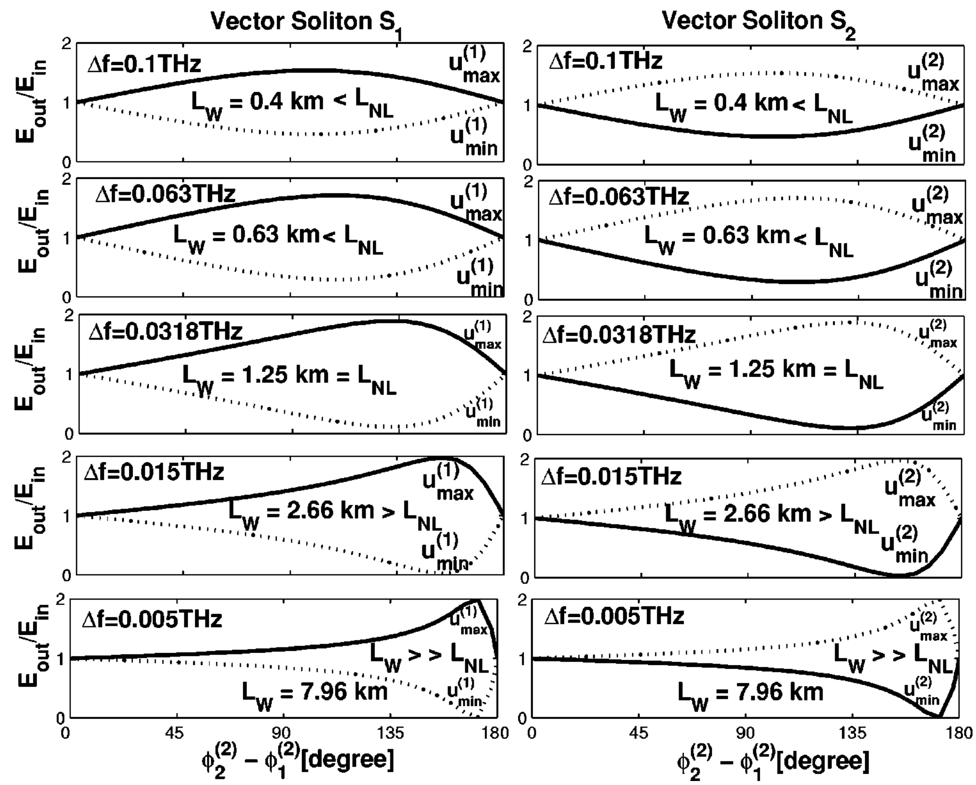

FIG. 1. Initial phase difference between the components of S_2 (or the state of polarization of S_2) is varied against the output and input energy ratio by fixing the initial phase difference of S_1 as 0° and θ=45° at different Δf values. Here Δt=56 ps.

gained energy as $u_{max}^{(1)}$ ($u_{max}^{(2)}$). Similarly we designate the component of soliton S_1 (S_2) which has lost energy as $u_{min}^{(1)}$ ($u_{min}^{(2)}$).

We start our discussion by raising the fundamental question that for a given Δf value, how sensitive is the energy-exchange process with respect to the initial polarizations of colliding solitons. To answer this question we have examined the energy ratio E_{out}/E_{in} between the energies of each component of the two solitons after (E_{out}) and before (E_{in}) the collision, as a function of $\phi_2^{(2)}-\phi_1^{(2)}$, for different values of Δf. In Fig. 1, for the different considered Δf values, the amount of energy transfer from one component to the other component of the colliding solitons is recorded at different initial phase differences of S_2 without modifying the other parameters defined above. Here we note the Manakov's observations [4] that there is no energy switching when $\theta^{(1)} = \theta^{(2)} = \theta = 45°$, and $\phi_2^{(2)}-\phi_1^{(2)}=180°$ (because, for this choice $\mathbf{C}^{(1)} \| \mathbf{C}^{(2)}$). We also observe in Fig. 1 that by increasing the value of $\phi_2^{(2)}-\phi_1^{(2)}$ from 0° to 180°, the efficiency of the energy transfer from one component to the other increases very slowly and reaches its maximum value in a different part of the $\phi_2^{(2)}-\phi_1^{(2)}$ range (depending on a given Δf value) and then decreases. In addition, one can note that this variation is not uniform for all given Δf values. That is, if the given Δf value is very small (say here, $\Delta f \leqslant 0.005$ THz) the maximum efficiency will appear suddenly at a particular value (very close to 180°), otherwise (when $\Delta f > 0.005$ THz) the efficiency will increase gradually and stand almost very close to its maximum value for a small range of $\phi_2^{(2)}-\phi_1^{(2)}$ variation. This range is broad for a large Δf value, namely, $\Delta f \geqslant 0.005$ THz. Further, one can observe that the value of $\phi_2^{(2)}-\phi_1^{(2)}$ giving the maximum switching efficiency depends strongly on the value of Δf. That is, each Δf value has different maximum possible switching efficiency at different $\phi_2^{(2)}-\phi_1^{(2)}$. For the such observed $\phi_2^{(2)}-\phi_1^{(2)}$ values at the different Δf values, Fig. 2 gives the values of energy of each component of the two vector solitons at the different fiber lengths. In general, as Fig. 2 shows, the energies of vector solitons S_1 and S_2 recorded at different fiber lengths clearly reflect that before the collision S_1 and S_2 are having equal energy distribution in their respective components. But after the collision, one of the components of each soliton gains energy from the other component. In our situation, when the gain appeas in one component of S_1 then the corresponding component in S_2 faces loss. For example, we see in Fig. 2, when Δf=0.1 THz, that the maximum possible switching efficiency (53.5%) occurs for $\phi_2^{(2)}-\phi_1^{(2)}=100°$. In this case the switching is partial or inefficient. This inefficiency increases if we increase the Δf value further. But our aim is to obtain the condition for high switching efficiency. This is achieved only by decreasing the Δf value. When Δf decreases the switching efficiency increases systematically as shown in Figs. 1 and 2. When Δf becomes sufficiently small the maximum efficiency appears at a certain critical value of $\phi_2^{(2)} - \phi_1^{(2)}$ (for an example when Δf=0.005 THz, 99.1% is achieved at $\phi_2^{(2)}-\phi_1^{(2)}=172°$ as shown in Figs. 1 and 2. This optimum value is very close to 180° where $\mathbf{C}^{(1)} \| \mathbf{C}^{(2)}$. Thus, the maximum switching efficiency appears very close to the situation where there is no switching. Here a fundamental question arises as to whether or not there is a discontinuity or

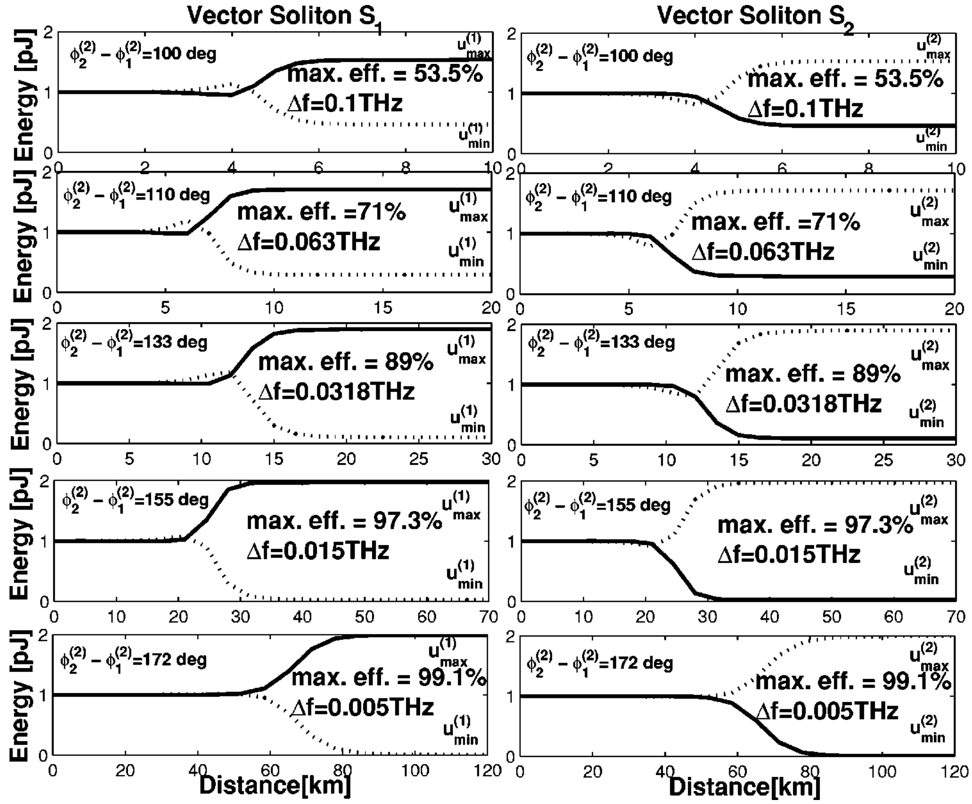

FIG. 2. The maximum possible switching efficiency at different Δf values is obtained by changing the initial phase difference of S_2 to a particular value Here $\Delta t = 56$ ps, $\theta = 45°$, and $\phi_2^{(1)} - \phi_1^{(1)} = 0°$.

sharp jumping between the switching and nonswitching parametric region. In order to answer this question, we have decreased the Δf value from 0.4 THz to 0.0005 THz and obtained 99.8% efficiency at $\phi_2^{(2)} - \phi_1^{(2)} = 179°$ as shown in Fig. 3. If Δf is decreased further, $\phi_2^{(2)} - \phi_1^{(2)}$ will move very close to 180° and there, the switching efficiency will jump into the situation ($\phi_2^{(2)} - \phi_1^{(2)} = 180°$, i.e., $\mathbf{C}^{(1)} \parallel \mathbf{C}^{(2)}$) where there is no switching. It is worth noting that when Δf is small then there is an overlap between the frequency spectrum of S_1 and S_2.

B. Relation between polarization and walk-off length

The reason for the above energy-exchange process can be explained phenomenologically by using the approximate re-

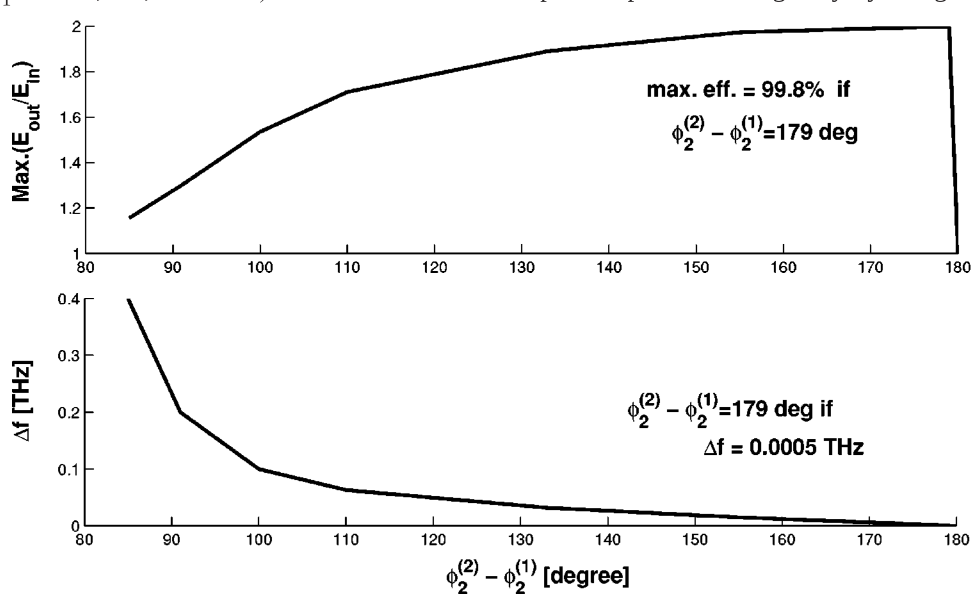

FIG. 3. Plot showing that the maximum efficiency appears very close to the situation where there is no switching. Thus there is an interesting jumping phenomenon or discontinuity between the switching (179 °) and nonswitching (180 °) region.

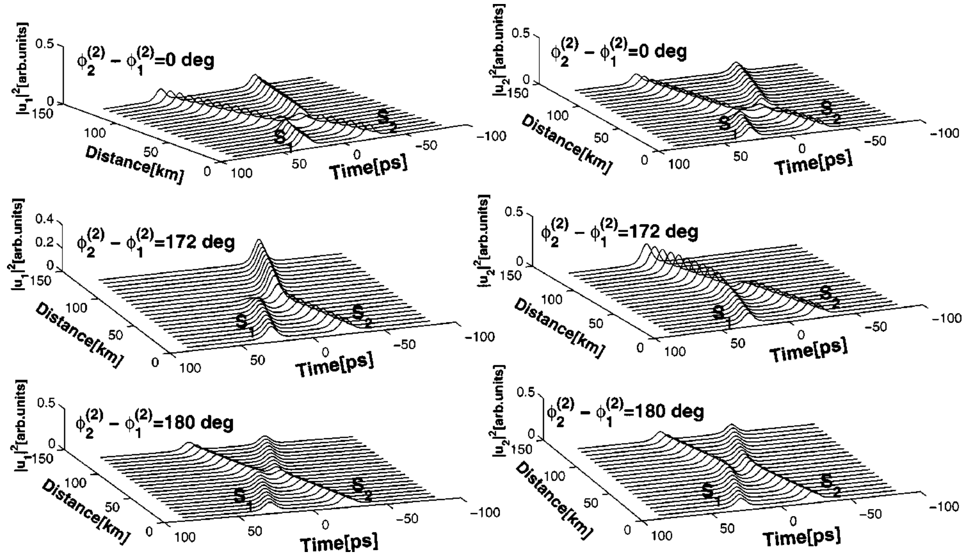

FIG. 4. Intensity plots showing the collision dynamics at different polarizations of S_2 with $\phi_2^{(1)}-\phi_1^{(1)}=0°$ and $\theta=45°$. Note that the collision appears at different fiber lengths and produced different position shifts. Here $\Delta t=56$ ps and $\Delta f=0.005$ THz.

lation for walk-off length (during which two overlapping pulses separate from each other), $L_W \approx \delta_0/(2\pi|\beta_2|\Delta f)$, where $\delta_0=(\delta_0^{(1)}+\delta_0^{(2)})/2$ is the average value of width of the two solitons. This relation gives the condition $\Delta f=1/2\pi\delta_0$, if the nonlinear length $[L_{NL}=1/\gamma P_0$, in which $P_0=(P_0^{(1)}+P_0^{(2)})/2$ is the average power of the two solitons], the dispersion length $(L_D=\delta_0^2/|\beta_2|)$, and L_W are equal. In the present study, we take $\delta_0=5$ ps, which imposes $\Delta f=0.0318$ THz under the condition $L_W=L_D=L_{NL}=1.25$ km. From Figs. 1 and 2 it is obvious that, if $\Delta f=0.0318$ THz, 89% efficiency is possible. This efficiency decreases if $L_W<L_{NL}$, and becomes decreasingly small for $L_W \ll L_{NL}$. Thus, we have found that, to increase the switching efficiency appearing at $L_W=L_D=L_{NL}$ to the highest value ($\approx$100%), one must choose the precollision parameters in such a way that

$$L_W \gg L_D = L_{NL}. \tag{3}$$

The simplest way to increase L_W without changing L_D and L_{NL} is to decrease Δf. Thus, for sufficiently small Δf, then $L_W \gg L_{NL}$, and there, the soliton interaction resulting from the collision process becomes slow. This slow interaction gives enough time for the nonlinear effects to play a significant role during the collision process, thus creating the maximum switching efficiency. However in the extreme case, when $L_W \to \infty$, which corresponds to $\Delta f=0$, there is no energy-exchange collision due to the fact that the two solitons having the same frequency value do not collide. Also it is worth noting that in the particular case $\Delta f=0$ and $\Delta t=0$ (not represented in the figures), a peak-power fluctuation occurs during the soliton propagation. Indeed, when S_1 and S_2 are launched from the same temporal window without any frequency mismatch, S_1 and S_2 influences each other throughout the propagation. Thus, our results in Figs. 1 and 2 demonstrate that an appropriate choice of walk-off length is needed to get the maximum efficient energy exchange due to the Manakov vector-soliton collision. In addition, it is interesting to note that the role of the polarization of S_1 and S_2 also depends on L_W. That is, when $L_W \gg L_{NL}$, the polarization of each colliding soliton becomes sensitive and can be tuned to the optimum value to get the maximum energy exchange as shown in Fig. 1, whereas the role of polarization is not significant at all when $L_W \gg L_{NL}$. For the intermediate values of L_W (i.e., $L_W<L_{NL}$ or the order of L_{NL}) the range of the initial phase difference of any one of the colliding solitons (over which the maximum possible switching efficiency appears) is not critical. From Fig. 1 one can see that this width is narrow if $L_W>L_{NL}$ and broad if $L_W<L_{NL}$. Thus, here we conclude that for a given L_W value, by simply tuning the phase of any one of the two colliding solitons or the state of polarization, one can substantially enhance the switching efficiency. But this tuning leads to 100% efficiency only if $L_W \gg L_{NL}$.

In other way, by decreasing the temporal pulse width of the colliding solitons for any given Δf value, one can also explain the above noted concepts. That is, an efficient energy switching starts when the pulse width is tuned to a certain optimum value for which $L_W \gg L_{NL}$. In addition, we verified that all the above results can also be obtained by choosing appropriate values for the 12 arbitrary parameters in the exact more general two-soliton solution of Eq. (1) derived by Radhakrishnan *et al.* in Ref. [13]. Hence the efficiency of energy switching depends not only on the initial frequencies and but also on the pulse widths of colliding solitons as shown by the relation for L_W.

By considering the $\Delta f=0.005$ THz case (where the 99.1% switching efficiency appears) we have represented the collision dynamics for different initial polarizations of S_1 and S_2, in Fig. 4. It is very interesting to note that the change of polarization does not affect the walk-off length, but increases the switching efficiency. Further, the complete energy switching is observed simultaneously in the two colliding vector solitons when the initial state of polarizations of S_1 and S_2 corresponds to $\phi_2^{(1)}-\phi_1^{(1)}=0$, $\phi_2^{(2)}-\phi_1^{(2)}=172°$. In earlier studies [13,14,21], one soliton is used to stimulate com-

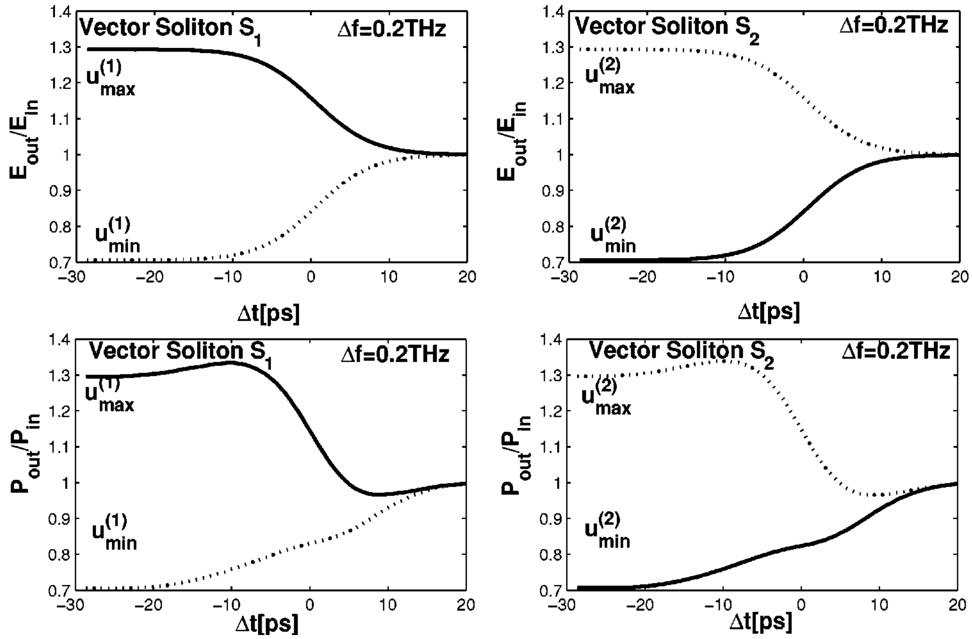

FIG. 5. Plots showing the energy and peak power gain and loss in the components of S_1 and S_2 after they collide at different Δt values. Here the values for polarization parameters are $\theta=45°$, $\phi_2^{(1)}-\phi_1^{(1)}=0°$, and $\phi_2^{(2)}-\phi_1^{(2)}=90°$ and $L_W=0.2$ km.

plete switching in the other soliton by collision. Let us compare the collision dynamics for $\phi_2^{(2)}-\phi_1^{(2)}=0$ and $\phi_2^{(2)}-\phi_1^{(2)}=180°$ as shown in Fig. 4. In these two cases there is no energy transfer but the collision dynamics looks attractive in the former case and repulsive in the latter case. Throughout this study, by just varying the phase of S_2, we have observed an important efficient energy switching. The same behavior can be observed by varying the polarization angle. In such a case, the initial energy distributions among the soliton components would not be the same. Anyhow, whatever be the initial energy distribution, the soliton's power [defined in Eq. (2)] can be scaled to any desired value without affecting the given properties and any of the other parameters associated with vector solitons. The present study can also be tailored to any given parametric choice. The allotted values for the arbitrary parameters have been chosen just as an example of parameter set.

C. Influence of the initial time delay

We now consider the behavior of the energy switching with respect to the initial time delay Δt. For this purpose we consider the case $\Delta f=0.2$ THz, where the frequency spectra of the colliding solitons are clearly separated, so that the energies of the two solitons (component wise) can be easily evaluated throughout the propagation (including the collision region) by using a frequency filter. Further, here, we take S_2 as the slow soliton and S_1 as the fast soliton by choosing $f_1>f_2$ with $\Delta f=0.2$ THz (just for convenience). In Fig. 5 the input and the output energies and peak powers of the colliding solitons at different Δt are compared. Whatever be the initial time delay between the colliding solitons the sum of the energy in u_1 and that in u_2 of each colliding soliton is always 2 pJ. However, if $|\Delta t|\lesssim\delta_0=5$ ps, the closely packed colliding solitons execute partial collision, which truncates the walk-off length. Due to this partial collision the energy transfer efficiency decreases as shown in Fig. 5, but solitons always have their initial energy value $E_{in}=2$ pJ. This reflects the principle of energy conservation as one expects for such a conservative system for all Δt. Beyond a certain Δt value, the fast soliton S_1 first appears before the slow one. Therefore no collision takes place and the initial energy distribution among the soliton components is maintained as shown in Fig. 5.

But in Fig. 5 the sum of peak powers in the u_1 and u_2 components of the colliding solitons are not always equal to its initial value $P_{in}=0.2$ W after the collision if $|\Delta t|\lesssim\delta_0$. But in this region, the energy is conserved as explained before. It reflects that there is a pulse broadening when the peak power in the components of the each colliding soliton decreases or there is a pulse compression when the peak power in the components of each colliding soliton increases. For example, we have examined the collision behavior when vector solitons are closely packed, as shown in Fig. 6. It clearly shows that the sum of the peak powers in the u_1 and u_2 components of the colliding solitons is less than 0.2 W after collision, and thus not conserved, whereas the energies of the colliding solitons are conserved throughout the collision dynamics. Therefore one can conclude that the colliding solitons experience pulse broadening after collision. Further one can note from Figs. 5 and 6 that such a pulse broadening is not uniform in the components of S_1 and S_2. This shows that if the vector solitons of the integrable Manakov model are closely packed and then allowed to collide, nonuniform pulse broadening will take place. It is surprising to observe such a behavior in an integrable $(1+1)$ dimensional system. In literature [4,13,14] so far, it was claimed that except the polarization of colliding Manakov-like vector solitons, there is no other change in soliton parameters during collision. It is

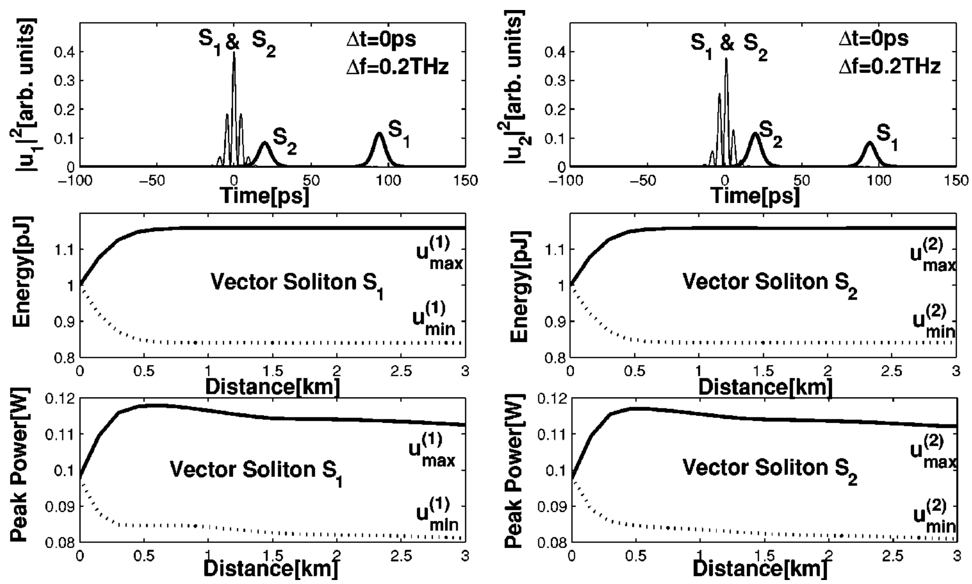

FIG. 6. Closely packed vector solitons undergo overtaking collision.

proved here that this is true only if L_W is not truncated during the collision dynamics

IV. CONCLUSIONS

In conclusion, we have examined the behavior of energy-exchange process within vector solitons undergoing collisions in different physical situations. It comes out that an appropriate choice of soliton parameters is needed to produce the maximum energy exchange. Such results are particularly interesting from the practical point of view. Indeed Manakov solitons are not only mathematical concepts, but have also been observed in recent experiments [6–8,15]. We have also observed that by tuning the phase of any one of the colliding solitons to a certain optimum value one can get essentially 100% switching efficiency provided $L_W \gg L_{NL}$. For $L_W > L_{NL}$, the magnitude of the initial phase difference of any of the colliding solitons (over which a maximum possible switching efficiency appears) is not critical but narrow, while the width is broad if $L_W < L_{NL}$. However the phase parameters will not play any significant role in the enhancement of the switching process if $L_W \ll L_{NL}$. In addition, for a given Δf, one can vary the switching efficiency without disturbing the walk-off length. Further, the complete energy switching is observed simultaneously in the two colliding vector solitons as shown in Fig. 4 whereas one soliton is used to stimulate complete switching in the other soliton by collision in Refs. [13,14,21]. Moreover, we have observed surprising changes in the pulse width if L_W is truncated during the collision dynamics governed by the practically interesting integrable Manakov model.

ACKNOWLEDGMENTS

R.R. acknowledges the Ministére de la Recherche and G.M. acknowledges the Institut Universitaire de France for financial support. The Centre National de la Recherche Scientifique and the Ministére de la Recherche et des Nouvelles Technologies are gratefully acknowledged for their support. The Jamal Mohamed College is gratefully acknowledged by R.R. for the encouragement.

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