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All-optical serial switcher

F. GARZIA, C. SIBILIA AND M. BERTOLOTTI
INFM Dipartimento di Energetica, Università degli Studi di Roma "La Sapienza", Via A.Scarpa 16, 00161 Rome, Italy (E-mail: garzia@uniroma1.it)

Abstract. We present a device that is capable of switching a sequence of equally spaced pulses between two or more outputs, according to the switching information carried from the first pulse, that behaves as an addresser. The device acts as an all-optical serial switcher and it is based on the properties of a soliton beam in a transverse refractive index profile. We further study the interaction force between solitons.

Key words: all-optical device, all-optical switching, soliton interaction, spatial soliton

1. Introduction

Spatial soliton are very useful to design optical switches and some proposals have been considered using their interesting interaction properties and the waveguide structures induced by these interactions (Ciao *et al.* 1964; Gordon 1983; Luther-Davies *et al.* 1992a, b; Akhmediev *et al.* 1993; Sheppard *et al.* 1993; Yang *et al.* 1993; Garzia *et al.* 1994; Krolikowski *et al.* 1994; Krolikowski *et al.* 1996). The interesting properties of solitons, allow to design a variety of helpful devices.

Attractive effects have been found in the study of transverse effects of soliton propagation at the interface between two non-linear materials (Aceves *et al.* 1988, 1990; Varatharajah *et al.* 1989) or in a material in the presence of a Gaussian refractive index profile, that is in low perturbation regime (Garzia *et al.* 1997, 1998).

It has been shown that it is possible to switch a soliton, in the presence of a transverse refractive index variation, towards a fixed path, since the index variation acts as a perturbation against which the soliton reacts as a particle, moving as a packet without any loss of energy.

In this paper we study a device that is able of switching a sequence of equally spaced pulses between two or more outputs, using as commutation information the value of the relative phase of the first pulse with respect to the others. This kind of device has already been studied (Garzia *et al.* 1999), with the only limitation that the switching mechanism, owed to the solitons beams, was determined by means of direct numerical simulations. In this paper, we improve it using an 'empirical' method that allows to determine the interaction force between two parallel solitons as a function of their relative distance and of their relative phase. Using these results, we design an optical device that we tested by means of numerical simulations.

In our geometry a soliton beam travels in a waveguide which, in the plane between the cladding and the substrate, has a distribution of refractive index which follows a triangular curve, with a longitudinal parabolic profile, as shown in Fig. 1.

We start by studying the general structure of the device. Then the transverse behaviour of a soliton in a triangular profile, whose longitudinal profile is parabolic, is examined. Then we determine the interaction force between solitons. Once the properties of motion are derived, we investigate the structure from the global point of view, deriving all the properties that represent the scope of this paper.

2. Structure of the serial switcher

To simplify the development of the theory, we consider only a 1 input–2 outputs device. The purpose of the device is to switch a train of equally spaced pulses from one output to the other according to the address information carried by the first pulse of the train, called addresser pulse, to realise an optical router. We suppose to work with soliton beams to use their attracting or repelling properties (Gordon 1983) and their particular behaviour when they propagate in a transverse refractive index profile (Garzia *et al.* 1998, 1999). The structure we want to study is shown in Fig. 1.

The working principle is the following: when a train of pulse must be switched from one output to the other a proper phase soliton pulse is sent before the whole train, with the same temporal interval of the pulses that compose the train. The first pulse that enters the device is the addresser pulse. The loop waveguide is composed by two branches of a suitable lon-

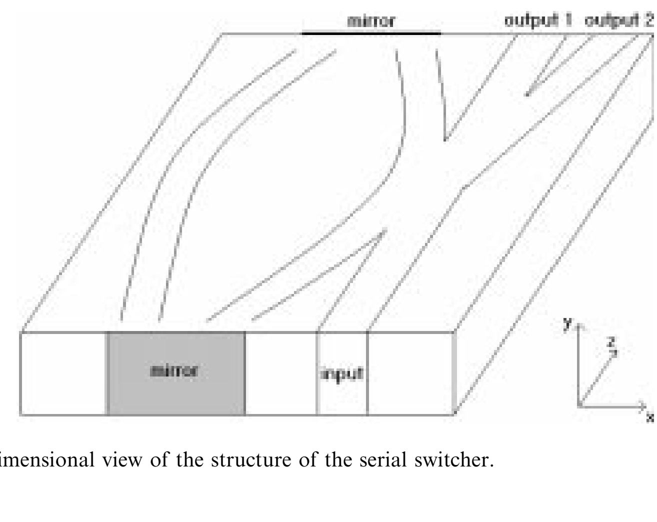

Fig. 1. Three-dimensional view of the structure of the serial switcher.

gitudinally parabolic waveguide and two mirrors. If the refractive index of the parabolic waveguide is a bit higher than the one of the main waveguide and if the curvature of the loop waveguide is the right one (as we will show later) the addresser pulse is attracted towards the loop waveguide, entering in it. If the intensity of the addresser soliton is above a certain level, it propagates in the loop, reaching the starting point after a certain time, called loop time, that is chosen to be equal to the temporal interval between two sequential pulses of the train. At this point the addresser pulse propagates quasi-parallel to the first pulse of the train that has entered the waveguide. This pulse is attracted towards the loop waveguide: if we want it to propagate undisturbed to reach the first output we have to act a slightly repulsive action for the time necessary to pass the point where the two waveguides merge. If, on the contrary, we want the pulse to reach the output 2, it is necessary to produce a strong repulsive action. This can be done using the properties of repulsion of two close and parallel soliton with a relative phase ranging between $\pi/2$ (no action) and π (maximum repulsive action). The two phase values, corresponding to the slight or to the strong repulsive action, have to be chosen in this interval, according to the refractive index difference between the main and the loop waveguide. After the first pulse has been correctly switched, the addresser pulse makes another trip in the loop, reaching the merging point when another pulse of the train is present and producing a new switch. This commutation process continues until all the pulses of the train have arrived. At this point it is necessary to exit the addresser pulse from the loop. Until now we have neglected the absorbing action of the material, that, trip after trip, has decreased the intensity of the addresser pulse. If the intensity of this pulse is properly over-dimensioned, so that it decreases to a certain value after a number of trips that is equal to the number of pulses that composes the train, the pulse has its power so lowered that does not remain locked inside the loop waveguide, leaving it and letting it free of accepting a new addresser pulse.

We will now define better the profile of the refractive index of the waveguides and the properties of the longitudinal parabolic waveguides that compose the loop.

3. Properties of a soliton in a longitudinal parabolic waveguide

We want now to define the structure of the parabolic waveguide composing the loop to find its peculiar properties that allow the loop to work properly. We choose this kind of waveguide because it is the simplest curve that takes progressively the soliton beam to the merging point of the waveguides and then again into the loop. This path could be roughly approximated with a linear and oblique curve, but the final result would be a too sharp path, that disturbs the repulsive effect that takes place into the merging point. Further the parabolic path is the trajectory followed from a soliton beam that is injected into a triangular transverse refractive index profile, that is the transverse profile that we are going to consider.

Let us consider a soliton beam propagating in the z-direction, whose expression of the field Q at the beginning of the structure is:

$$Q(x,0) = C\,\mathrm{sech}[C(x-\bar{x})], \tag{1}$$

where $\bar{x}$ is the position of the centre of the beam and C is a real constant from which both the width and the amplitude of the field depend. The variables x and z are normalised with respect to the wavevector of the wave and therefore they are not dimensional.

When the soliton beam is propagating in a triangular transverse index profile, whose maximum value is Δn_0 and whose maximum width is $2b$, it is subjected to a transverse acceleration equal to (Chen and Liu 1978; Cow 1982; Garzia *et al.* 1998):

$$a_{\mathrm{T}} = \frac{2\Delta n_0}{b}C^2. \tag{2}$$

We use, for our analysis, a dynamic point of view, that is to consider the step by step transverse relative position of the waveguide with respect to the beam using the z variable as a time parameter. If $x_{\mathrm{G}}(z)$ is the position of the central part of the waveguide profile with respect to z, the longitudinal expression of the waveguide is chosen to be parabolic and its expression is:

$$x_{\mathrm{G}}(z) = az^2, \tag{3}$$

where a is a real constant responsible for the curvature of the waveguide.

Under these conditions, the local inclination of the waveguide with respect to the longitudinal axis z, can be regarded as the transverse relative velocity of the waveguide that appears to the beam that propagates longitudinally:

$$v_{\mathrm{G}} = \frac{\mathrm{d}x_{\mathrm{G}}(z)}{\mathrm{d}z} = 2az. \tag{4}$$

Using Equation (2) it is possible to calculate the transverse relative velocity:

$$v_{\mathrm{B}} = \int_0^z a_{\mathrm{T}}\,\mathrm{d}\zeta = \frac{2\Delta n_0}{b}C^2 z \tag{5}$$

and the position of the beam:

$$x_B = \int_0^z v_B \, d\zeta = \frac{\Delta n_0}{b} C^2 z^2. \tag{6}$$

Initially the beam is positioned in the centre of the waveguide. Since the waveguide appears to move with respect to an observer that follows the longitudinal direction with a relative velocity expressed by Equation (4), the soliton beam enters in the constant acceleration zone, where its velocity increases linearly with z. It also follows a parabolic trajectory, according to Equation (6), until it remains in this part of the waveguide.

After that the beam has propagated for a certain z distance, two different situations may happen: the beam leaves the acceleration zone without reaching the velocity of the waveguide at that z, or the beam acquires a velocity that is greater than or equal to the velocity of the waveguide. The first event may be called 'detach situation', since the beam leaves the waveguide, while the second one may be called 'lock-in situation' since the beam reaches the other side of the waveguide where it is stopped, reversing its path and so on.

At any value of z, as shown in Fig. 2, the distance d_{GB} between the waveguide and the beam is:

$$d_{GB} = x_G - x_B = az^2 - \frac{\Delta n_0 C^2}{b} z^2 = \frac{ab - \Delta n_0 C^2}{b} z^2. \tag{7}$$

A detach situation takes place when:

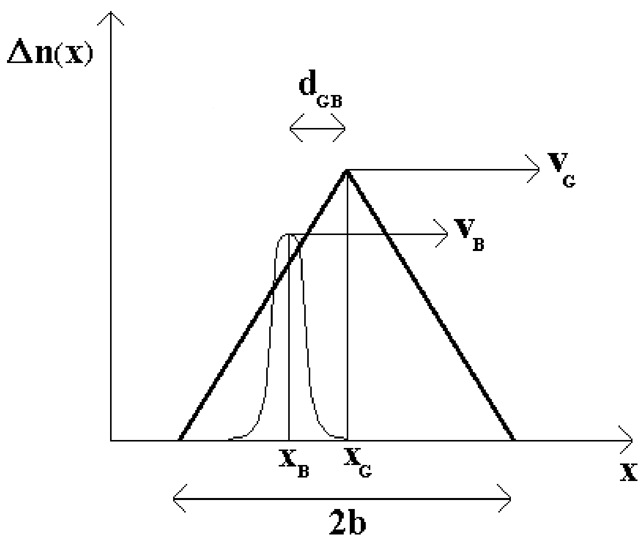

Fig. 2. Relative distance waveguide-soliton at some propagation distance z.

$$d_{GB} = b. \tag{8}$$

If we solve Equation (8) with respect to z we can calculate, if it exists, the propagation distance where the detachment begins:

$$z_D = \frac{b}{(ab - \Delta n_0 C^2)^{1/2}}. \tag{9}$$

From Equation (9) it is possible to calculate the value C_D of the amplitude that divides the lock-in values from the detach values:

$$C_D = \left(\frac{ab}{\Delta n_0}\right)^{1/2}. \tag{10}$$

It is possible to see, from Equation (9) that the more width of the profile (b parameter) or the curvature of the waveguide (a parameter) increase or the more the refractive index decreases, the more C_D increases. This behaviour agrees with what one could expect.

We want now to calculate the inclination according to which a soliton, whose amplitude is smaller than the detach amplitude, leaves the waveguide. Since the mentioned angle is equal to the detach velocity, substituting Equation (9) into Equation (5), we have:

$$\Phi = a\tan(v_D) \tag{11a}$$

and

$$v_D = v_B(z_D) = \frac{2\Delta n_0 C^2}{(ab - \Delta n_0 C^2)^{1/2}}. \tag{11b}$$

In Fig. 3 the graphical behaviour of Equation (11) for $a = 1 \times 10^{-3}$, $b = 4$, $\Delta n_0 = 1 \times 10^{-3}$ is shown. The detach value C_D can be calculated by Equation (10) and it is equal to 2.

Since we deal with a parabolic waveguide, we are in the presence of a curvature, with respect to the z axis, that increases with z. We have not to forget that we are in a paraxial approximation, that is the derived equations are valid until the angle between the propagation direction and the longitudinal direction is lesser than 8°–10°. This means that, due to the analytical expression of the waveguide, expressed from Equation (3), once the a parameter has been chosen, the propagation variable z can reach a maximum value over which the paraxial approximation is no more valid. In analytical terms it means that it is possible to impose this condition to the

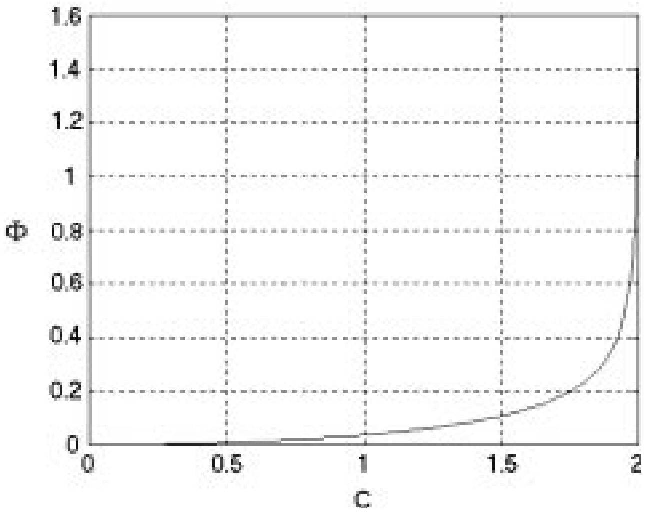

Fig. 3. Detach angle Φ in degrees, equal to atan(v_D), versus C for $a = 10^{-3}$, $b = 4$, $\Delta n_0 = 1 \times 10^{-3}$. The detach value is $C_D = 2$.

first derivative of Equation (3) to calculate the maximum propagation distance:

$$x'_G(z_{\max}) = \tan 8^\circ = 0.14 = 2az_{\max}, \tag{12}$$

that can be solved with respect to $z_{\max}$ giving:

$$z_{\max} = \frac{7 \times 10^{-2}}{a}. \tag{13}$$

Substituting Equation (13) into Equation (3) it is possible to calculate the correspondent $x_{\max}$:

$$x_{\max} = \frac{4.9 \times 10^{-3}}{a}. \tag{14}$$

This means that, once a parabolic profile has been chosen through the a parameter, the soliton can propagate in it for a maximum distance equal to $z_{\max}$. This condition must be considered in the project of the loop waveguide.

Once determined the propagation properties of a soliton beam in the loop waveguide it is necessary to determine the expression of the interaction force between solitons that represents the base of the switching effect used in our device.

4. Structure used for the determination of the interaction force between solitons

The determination of the attraction and repulsion force between two parallel solitons as a function of their relative phase and of their relative distance is quite difficult (Gordon 1983). It is only possible to know that it is a cosinusoidal function of the relative phase and an exponential function of their relative distance, but it is not possible to know anything else. Further, it has been demonstrated to be valid only in weak interaction conditions that is the two solitons are a bit partially overlapped.

We want now to determine, by means of an 'empirical' method, the interaction force as a function of the relative phase and of the relative distance of a couple of solitons even in strong interaction conditions.

The 'empirical' method used is based on choosing a particular transverse index profile, whose it is possible to determine the acceleration imposed to a soliton beam that propagates inside it, and to propagate inside it two parallel solitons, characterised by different relative phase and distance. The profile is chosen so that if the solitons attract each other it tends to separate them and vice versa. The magnitude of the profile is changed and the propagation is initialised again until the index action exactly balances the interaction force between solitons: in this situation the force imposed by the index profile (analytical determined) is equal to the opposite force imposed by the interaction between solitons. The simulations were made for different values of relative phases and relative distances, obtaining an analytical formula.

Since the attraction force varies in a cosinusoidal way (Gordon 1983) it is possible to concentrate the research on the attractive interval 0–$\pi/2$ or equally on the repulsive interval $\pi/2$–π, obtaining the same results. We concentrate on the attractive interval and we decide to use a linear index profile since a soliton beam that propagates inside it presents a constant acceleration given from Equation (2).

Since we choose to study the attractive interval, the slope of the linear index profile must be reversed, changing the sign of expression (2). The simulated structured is shown in Fig. 4.

5. Numerical simulation of the structure

We have simulated the structure using a FD-BPM algorithm to determine the interaction force. Different simulations were made varying the relative distance and the relative phase to deduce the behaviour of the interaction force that is a function of these two variables.

Once fixed a couple distance-phase, different sequences of simulations was made until the two beams propagates without changing their distance. The equilibrium condition is checked not only controlling the distance between

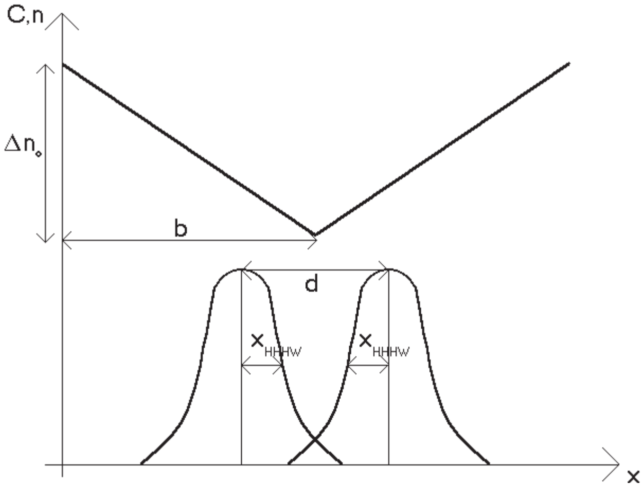

Fig. 4. Structure used for the determination of the interaction force.

the two peaks of the beams, but even controlling the stability of their profiles. In fact, since we are in the presence of two opposite forces, it may happens that the two solitons deform their profiles, keeping fixed the position of their maximums, that is the forces do not balance exactly each other even if it the contrary appears to happen. The maximum allowed variation of the profile, calculated as the sum of the relative errors, has been chosen to be 10^{-2}. These relative errors are calculated for each point, as the absolute value of the difference between the value of the beam profile at the begin of the simulation and the actual value of the beam profile during the simulation, divided by the first term of the difference.

Using this method, it could virtually be possible to vary the relative distance starting from a quasi total overlapping condition of the two beams. This was not possible in practice since, owed to the strong attractive force between the two solitons, it is necessary to apply a high refractive index profile. Since the force due to the soliton is a local force that acts only in the overlapping zone while the force due to the index profile acts all over the beam, it generates a local gradient that strongly deforms the beams, invalidating the 'empirical' measure.

The first useful relative distance has demonstrated to be the half height half width x_{HHHW} that is the distance from the centre of the beam where the amplitude reduces to one half, using Equation (1) it is possible to demonstrates that:

$$x_{\mathrm{HHHW}} = \frac{1}{C} \log(2 + \sqrt{3}), \tag{15}$$

that is a function of the amplitude C. This is quite obvious since C parameters is also present in the argument of the hyperbolic secant function, that is the more the amplitude C increases, the more the width of the beam decreases and vice versa. This also implies that to obtain a general result, once chosen a couple distance-phase, it is necessary to find the different interaction forces as a function of C. This implies to increase further the number of simulations. The minimum value of the relative distance d has therefore been considered to be equal to twice the half height half width.

Owed to the high number of simulations necessary to validate the results of the 'empirical' method used, an automatic procedure has been implemented. Once chosen a value for C parameter in a given interval, the procedure resizes the dimensions of the transversal simulation window, to use it as efficiently as possible, and starts to simulate with different increasing values of the relative distance d, chosen in the interval of $2x_{\mathrm{HHHW}} \leq d \leq 6x_{\mathrm{HHHW}}$. For each value of d, different increasing values of relative phase ϕ are chosen in the interval $0 \leq \phi \leq \frac{\pi}{2}$, and for each value of ϕ different simulations have been made automatically until finding a value of Δn_0 that let the index force to balance the attraction force between the two solitons.

The values of C parameter have been chosen in the 5 decades interval $10^{-2} \leq C \leq 10^2$, and for each decade, 10 unitary values belonging to it have been chosen, that gives a total of 50 values of C parameter. For each value of C parameter, the relative distance d has been varied from $2x_{\mathrm{HHHW}}$ to $6x_{\mathrm{HHHW}}$ in steps of $0.5x_{\mathrm{HHHW}}$, that gives a total of 9 values of d. For each value of C and d, the relative phase ϕ has been varied from 0 to $\pi/2$ in steps of $\pi/16$, that gives a total of 9 values of ϕ. The total number of simulations made is therefore equal to the product of the number of values of C parameter, multiplied for the number of values of d, multiplied for the number of values of ϕ, that gives a total of 4050 simulations.

The non-equilibrium simulations must be added to this number, even if they are immediately interrupted by the simulation system as soon as it encounters this kind of situation, calculated according to the criterion already exposed.

In Fig. 5 the situation of stronger index force with respect to the attraction force, implying beams diverging, the situation of weaker index force with respect to the attraction force, implying beams converging and the situation of balance between the two antagonist forces, implying beams equilibrium, are shown.

We have not to forget that we are in a paraxial approximation, that is the derived equations are valid until the angle between the propagation direction and the longitudinal direction is lesser than 8°–10°. Anyway, the equilibrium condition is a paraxial free propagation situation and no particular restriction is imposed. The correctness of the equations of motion (5–6) has further been demonstrated during simulations, when the index force is stronger with

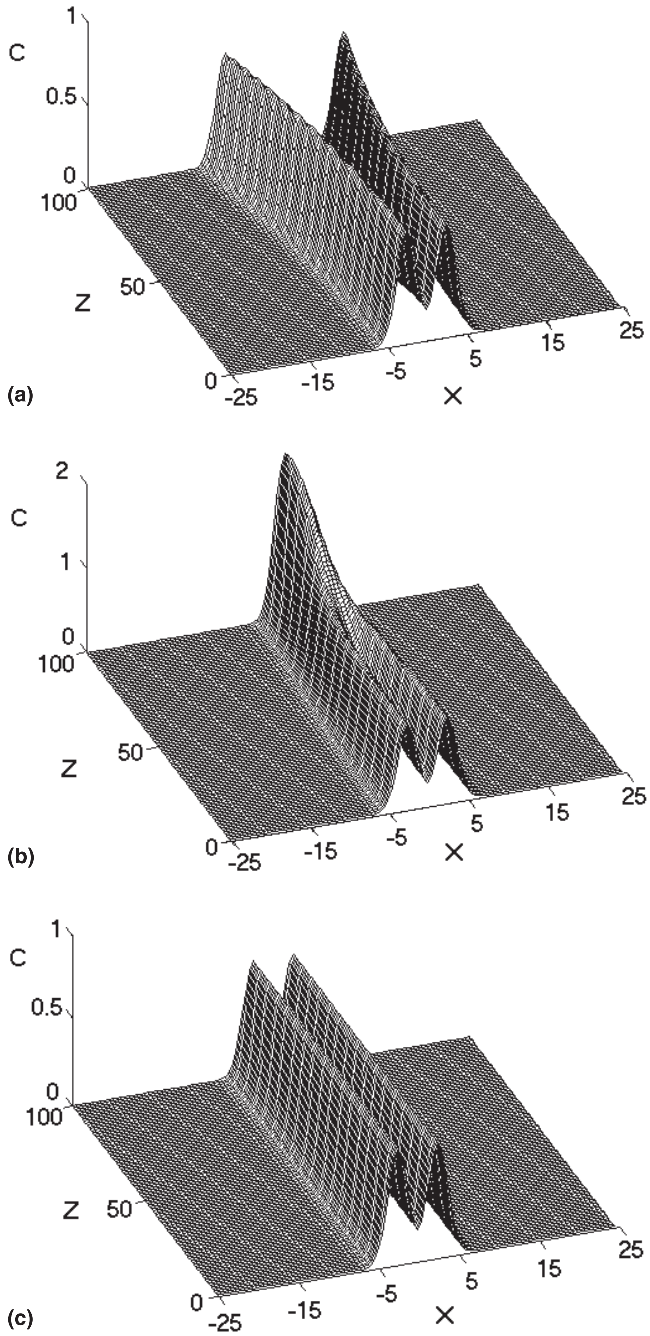

Fig. 5. (a) Numerical simulation for $C = 1,\ \phi = 0.935\pi/2,\ d = 5,\ \Delta n_0 = 6.75 \times 10^{-2},\ b = 25$. The index force is stronger than the attraction force and the beams diverge. (b) Numerical simulation for $C = 1,\ \phi = 0.935\pi/2,\ d = 5,\ \Delta n_0 = 1.25 \times 10^{-2},\ b = 25$. The index force is weaker than the attraction force and the beams converge. (c) Numerical simulation for $C = 1,\ \phi = 0.935\pi/2,\ d = 5,\ \Delta n_0 = 2.38 \times 10^{-2},\ b = 25$. The index force is equal to the attraction force and the beams propagate parallel each other.

respect to the attraction force, and the beams are free to be accelerated by the index profiles.

6. Results

Since we expect, according to the general theory (Gordon 1983), that the interaction acceleration, that we briefly call force, is an exponential function of the relative distance and cosinusoidal function of the relative phase, we use this kind of function in a least squares procedure, that is to find the best values of the two parameters P_1, P_2 of the following expression:

$$a(d, \phi, P_1, P_2) = P_1 \exp(-P_2(d - 2x_{\mathrm{HHHW}})) \cos \phi, \quad (d \geq 2x_{\mathrm{HHHW}}) \tag{16}$$

with a given quadratic error ε^2, for each singular point, given by the square of the difference between the value of the searched curve and the value found by means of the simulations, that we have fixed to be $\varepsilon^2 < \left|2.5 \times 10^{-5} C^4\right|$.

The least squares method applied to the Equation (16), respecting the given error, gives $P_1 = C^2/5$ and $P_2 = C$, and the resulting expression is:

$$a(d, \phi) = \frac{C^2}{5} \exp(-C(d - 2x_{\mathrm{HHHW}})) \cos \phi, \quad (d \geq 2x_{\mathrm{HHHW}}) \tag{17}$$

with an error $|\varepsilon|$, for each point, that is lesser than $\left|5 \times 10^{-3} C^2\right|$.

In Fig. 6 the graphic of Equation (17) for the only attractive interval $(0 \leq \phi \leq \pi/2)$ and for the whole phase interval $(\pi/2 \leq \phi \leq \pi)$ using different perspective views are shown.

The obtained expression is very useful to design all optical devices where the switching properties are based on properly relative phased solitons, since the interaction force can to dimension the device. In fact if we anyway choose to make the device not to work in a quasi-total beams overlapping situation, in agreement with the limits of validity of Equation (16), the obtained results perfectly match with the developed method. It has therefore been found, according to a more qualitative weak interaction theory (Gordon 1983), that the interaction force is an exponential function of the relative distance and cosinusoidal function of the relative phase, with the great advantage that, in our case, we have been able to determine it even in strong interaction conditions.

The Equation (17) refers to the acceleration obtained using the normalised non linear Schroedinger equation that is:

$$2\mathrm{i}\frac{\partial Q}{\partial z} + \frac{\partial^2 Q}{\partial x^2} + 2|Q|^2 Q = 0. \tag{18}$$

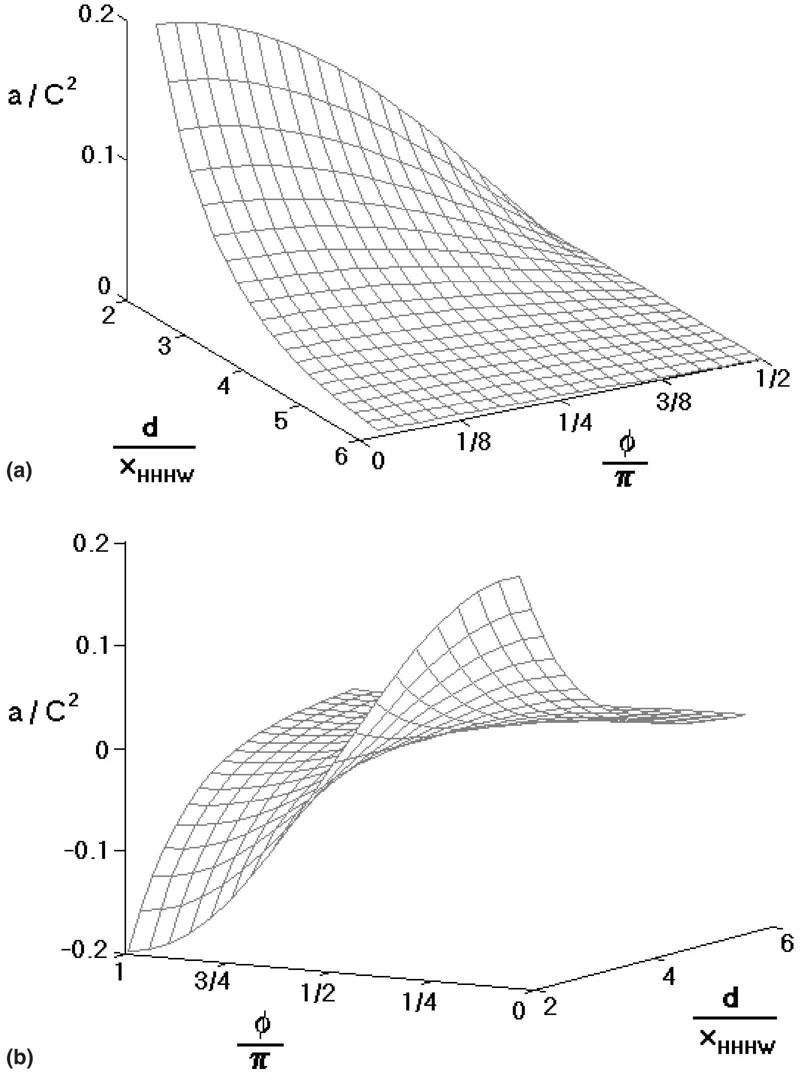

Fig. 6. (a) Graph of the interaction force as a function of the relative distance d and of the relative phase ϕ. The minimum relative distance d between the centres of the beams considered is equal to twice the half height half width $x_{\mathrm{HHHW}} = \log(2+\sqrt{3})$. The interval of values of relative phase ϕ considered is $0 \leq \phi \leq \pi/2$. (b) Graph of the interaction force as a function of relative distance d and of the relative phase ϕ. The minimum relative distance d between the centres of the beams considered is equal to twice the half height half width $x_{\mathrm{HHHW}} = \log(2+\sqrt{3})$. The interval of values of relative phase ϕ considered is $0 \leq \phi \leq \pi$.

If we want to express Equation (17) as a function of the refractive index n_0 of the nonlinear refractive index n_2, and of the wavevector $\beta = n_0(2\pi/\lambda)$, it is necessary to refer it to the ordinary non linear Schroedinger equation that is:

$$2\mathrm{i}\beta\frac{\partial A}{\partial Z}+\frac{\partial^2 A}{\partial X^2}+2\beta^2\frac{n_2}{n_0}|A|^2A=0, \tag{19}$$

that allows to calculate the normalised Equation (18) using the scale factors $x=\beta X, z=\beta Z, Q=A\sqrt{n_2/n_0}$. Introducing these scale factors into Equation (17) we have:

$$a(D,\phi)=\frac{n_2}{n_0}\frac{A^2}{5}\exp\left(-A\sqrt{\frac{n_2}{n_0}}\beta(D-2X_{\mathrm{HHHW}})\right)\cos\phi, \tag{20}$$

where D and X_{HHHW} are respectively the distance between solitons and the half height half width, both expressed in non normalised units.

7. Numerical simulation of the device

We want now to design the device, using all the developed theory until this point. The initial parameters of the loop waveguide are chosen to be equal to $\Delta n_0 = 1 \times 10^{-3}, b=1, a=1.5 \times 10^{-4}$ that give a detach value $C_{\mathrm{D}} \cong 0.4$. We therefore, choose the amplitude of the soliton beams to be equal to $C=1.5$. The index variation of the input waveguide is chosen to be $\Delta n_0 = 5 \times 10^{-4}$.

A beam propagating inside the main waveguide is attracted towards the loop waveguide with an acceleration a_{L} that can be calculated from Equation (2), where Δn_0 is the difference between the index variation of the loop waveguide and the index variation of the main waveguide. Substituting the numerical values we have $a_{\mathrm{L}} = 2.25 \times 10^{-3}$. Once we know the value of the acceleration that acts on a beam to attract it inside the loop waveguide, we have to choose, using Equation (16), a value for the distance d and for the relative phase ϕ_1 that allows an addresser soliton that propagates inside the loop to repel a data soliton with an acceleration that is exactly equal to the acceleration with which the loop index attract it. If we choose, for example $d = x_{\mathrm{HHHW}}$, we obtain from Equation (16) $\phi_1 = (\pi/2) + (1/40)\pi$. This is the first phase value of the addresser soliton that allows it to switch the data soliton towards output 1.

The disposition of the waveguide of the device is shown in Fig. 7a. We concentrate now on the switching towards the second output. We can say, at first approximation supposing a constant repelling action between the addresser soliton and the data soliton, that the repelling acceleration, using the disposition of waveguides shown in Fig. 7a, must cause a lateral shift equal to $x_{\mathrm{S}} = 1$ during an interacting propagation distance equal to $z_{\mathrm{S}} = 30$. Using Equations (2–6) we obtain that the acceleration must be equal to

$a_R = 2.2 \times 10^{-3}$, that is just the same value of the acceleration we found in the previous case. This is the only acceleration necessary to deflect the data soliton towards output 2 without considering the term related to the attraction towards the loop: the total repelling acceleration owed to the interaction between the addresser and the data soliton must be equal to the sum

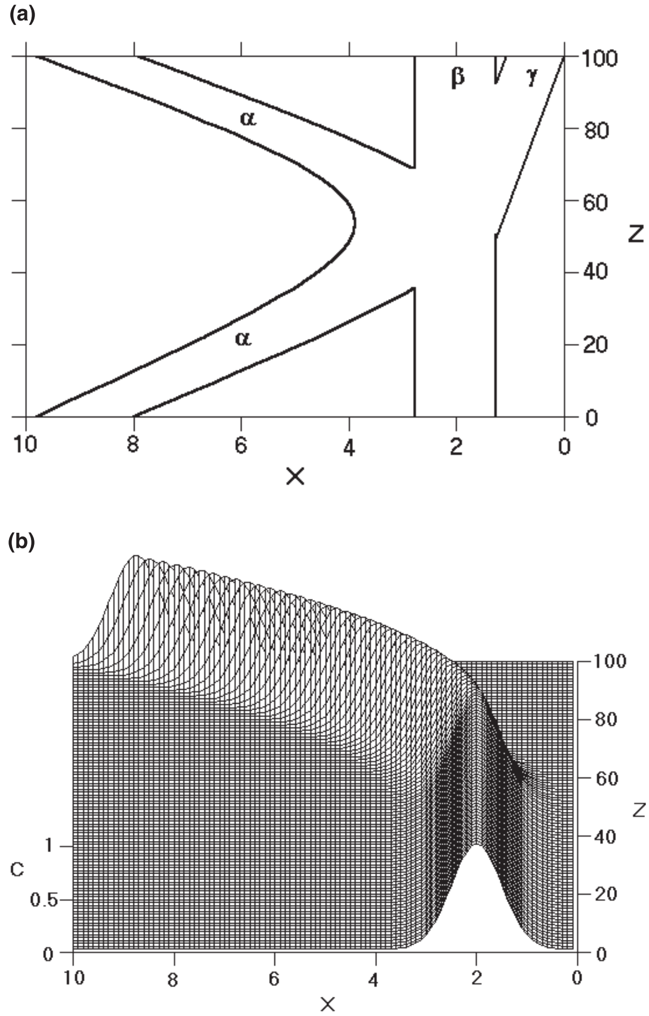

Fig. 7a,b Upper view of the structure and numerical simulations. The parameters of the waveguide are $\Delta n_0 = 1 \times 10^{-3}, b = 1, a = 1.5 \times 10^{-4}$. The detach value of the loop waveguide is $C_D \cong 0.4$. (a) Upper view of the structure. α is one half of the loop that is only partially represented here, β is the first output and γ is the second output. (b) Numerical simulation of the entrance, inside the loop waveguide, of the addresser soliton. The beam propagates until reaching the bifurcation point where it is attracted into the loop waveguide. This is the initial situation represented by the addresser soliton that precedes the data solitons to be switched.

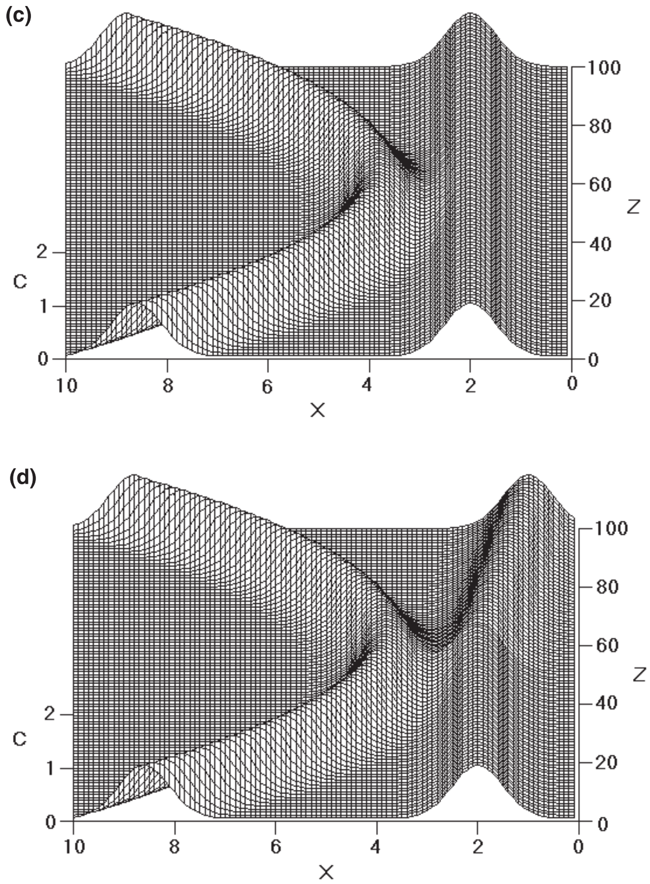

Fig. 7c,d (c) Numerical simulation of the commutation on the main waveguide (output 1), operated from the addresser soliton with respect to the data soliton. The relative phase difference between the two solitons is of $\pi/2 + \pi/40$. This is the situation where the addresser soliton, that propagates inside the loop waveguide (left side) and is characterized by a proper relative phase with respect to the data soliton (right side), switches the data solitons towards the first output (that is it makes the data soliton to proceed straight) by means of a weak repulsing action. (d) Numerical simulation of the commutation on the secondary waveguide (output 2), operated from the addresser soliton with respect to the data soliton. The relative phase difference between the two solitons is of $\pi/2 + 2\pi/40$. This is the situation where the addresser soliton, that propagates inside the loop waveguide (left side) and is characterized by a proper relative phase with respect to the data solitons (right side), switches the data solitons towards the second output by means of a strong repulsing action.

of these accelerations. Using Equation (16) we obtain $\phi_2 = (\pi/2) + (2/40)\pi$. Since we are in the presence of only two outputs it is possible to choose a phase value that enable the addresser soliton to switch the data soliton towards output 2 included between ϕ_2 and π, that is the maximum repelling action. If we are in the presence of more than two outputs, it is necessary to calculate a phase value for each exit.

Once designed the device and determined the operative phase values, we have finally simulated the device from the numerical point of view using a FD-BPM algorithm to study its behaviour and to see if it agrees with the above description. We only consider one half of the loop waveguide, since the most significant commutation effect takes place in the merging point of the two waveguides. The situations considered are the entrance of the addresser soliton inside the loop and the switching, operated from the addresser soliton with respect to the data soliton, in the main and in the secondary waveguides. The results are shown in Fig. 7.

In Fig. 7b, the entrance inside the loop waveguide is simulated. This happens, since the refractive index of the loop waveguide is higher than the refractive index of the main waveguide and the curvature of the loop (a parameter) allows the propagation of the soliton whose amplitude is greater than $C_D \cong 0.4$ ($C = 1.5$ in the simulation). In this case the beam is locked inside the waveguide as shown in Fig. 7a.

In Fig. 7c, the commutation on the main waveguide (output 1), operated from the addresser soliton with respect to the data soliton, is shown. The calculated relative phase difference $\phi_1 = (\pi/2) + (1/40)\pi$ between the addresser soliton and the data soliton generates a repelling acceleration exactly equal to the attraction acceleration of the loop. In this situation the data soliton is switched on the output 1 as it is desired while the addresser soliton remains locked inside the loop waveguide.

In Fig. 7d, the commutation on the secondary waveguide (output 2), operated from the addresser soliton with respect to the data soliton, is shown. The above calculated relative phase difference $\phi_2 = (\pi/2) + (2/40)\pi$ between the addresser soliton and the data soliton generates a repelling acceleration exactly equal to the sum of the attraction acceleration of the loop and of the acceleration necessary to spatially shift the data soliton towards output 2. In this situation the data soliton is switched towards the output 2, while the addresser soliton remains locked inside the loop waveguide. The considerations about practical design of this kind of device has already been made (Garzia *et al.* 1999) and they are not repeated here for brevity.

8. Conclusions

We presented and designed an all-optical serial switcher, based on the properties of soliton beams. We used, in particular, the property of repulsion between properly phased solitons whose we determined, using an 'empirical' method, the interaction force as a function of their relative distance and of their relative phase. We also studied the property of propagation in a longitudinal parabolic waveguide. The switching properties have been studied in details, obtaining some useful design criteria that help to design this kind of device. The serial switcher can be properly designed by means of the width, the curvature and the refractive index of the loop waveguide that compose the structure. The switching information is carried by the relative phase of the first pulse, called addresser pulse, whose intensity is properly increased with respect to the data pulses to allows it to propagate inside the loop waveguide a number of times equal to the number of data pulses to be switched. The number of outputs can be increased since the switching among them is ensured by controlling the relative phase of the addresser soliton with respect to the data solitons. The extension of the outputs does not influence the operative frequency that remains relatively high.

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