All optical router

F. Garzia, C. Sibilia, and M. Bertolotti

INFM Dipartimento di Energetica, Università degli Studi di Roma "La Sapienza", Roma, Italy

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 router 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.

Keywords: soliton interaction, all-optical switching, spatial soliton, all-optical device.

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[1-8]. 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 nonlinear materials[9-11] or in a material in the presence of a gaussian refractive index profile, that is in low perturbation regime[12,13].

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[14], 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 OPTICAL ROUTER

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[7] and their particular behaviour when they propagate in a transverse refractive index profile[14,15]. 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 longitudinally 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:

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

where $\overline{x}$ 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[13,15,16]:

$$a_T = \frac{2\Delta n_0}{b} C^2 . \tag{2}$$

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 $x_G(z)$ 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:

$$x_G(z) = az^2 , \tag{3}$$

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:

$$\mathrm{v}_G = \frac{dx_G(z)}{dz} = 2az . \tag{4}$$

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

$$\mathrm{v}_B = \int_0^z a_T d\zeta = \frac{2\Delta n_0}{b} C^2 z \tag{5}$$

and the position of the beam

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

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 eq.(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 eq.(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:

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

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

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

From eq.(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 eq.(9) that the more the 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 eq.(9) into eq.(5), we have:

$$\Phi = \mathrm{atan}\left(\mathrm{v}_D\right) \tag{11a}$$

and

$$\mathrm{v}_D = \mathrm{v}_B\left(z_D\right) = \frac{2\Delta n_0 C^2}{\left(ab - \Delta n_0 C^2\right)^{1/2}} . \tag{11b}$$

In fig. 3 the graphical behaviour of eq.(11) for a=$1 \cdot 10^{-3}$, b=4, $\Delta n_0 = 1 \cdot 10^{-3}$ is shown. The detach value C_D can be calculated by eq.(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 eq.(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 first derivative of eq.(3) to calculate the maximum propagation distance:

$$x'_G\left(z_{\max}\right) = \tan 8° = 0{,}14 = 2az_{\max} , \tag{12}$$

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

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

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

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

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[7]. 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 a mixed analytical-numerical technique, the interaction force as a function of relative phase and of relative distance of a couple of solitons even in strong interaction conditions.
The mixed analytical-numerical technique 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 (analytical part), and to propagate inside it two parallel solitons, characterised by different relative phase and distance (numerical part). 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[7] it is possible to concentrate the research on the attractive interval $0 \div \pi/2$ or equally on the repulsive interval $\pi/2 \div \pi$, 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 eq.(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). Therefore the two beams are partially overlapped in the middle of the simulations window where two reversed linear profiles start to grow, generating an opposite sign action. 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 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.
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 is limited only to 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 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 eq.(1) it is possible to demonstrates that:

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

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, that is to obtain a parameterised expression of interaction force, using C as a parameter. 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.
The systematic and complete number of simulations has shown that the interaction force is an exponential function of the relative distance and a cosinusoidal function of the relative phase according to the general theory[7] with the great advantage that, in our case, we have been able to determine it even in strong interaction conditions.
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.

6. RESULTS

All the simulations have demonstrated that the interaction acceleration, that we briefly call force, is an exponential function of the relative distance d and cosinusoidal function of the relative phase ϕ, according to the following equation:

$$a(d,\varphi)=\frac{C^2}{5}\exp\left(-C\left(d - 2x_{HHHW}\right)\right)\cos\phi\,, \qquad (d \geq 2x_{HHHW}) \tag{16}$$

where it is possible to see that it is not only a function of d and ϕ but also of C. The expression of the acceleration allows anyway to graph it as surface in a three dimensional space, using C as a parameter.

In figs.5 the graphic of eq.(16) for the only attractive interval (0≤φ≤π/2) and for the whole phase interval (π/2≤φ≤π) 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 eq.(16), the obtained results perfectly match with the developed method.

It has therefore been found, according to a more qualitative weak interaction theory[7], 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.

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 $\Delta n_0 = 1\cdot 10^{-3}$, b=1, a=$1.5\cdot 10^{-4}$ that give a detach value $C_D \cong 0.4$. 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 $\Delta n_0 = 5\cdot 10^{-4}$.

A beam propagating inside the main waveguide is attracted towards the loop waveguide with an acceleration a_L that can be calculated from eq.(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 $a_L = 2.25\cdot 10^{-3}$. 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 eq.(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_{HHHW}, we obtain from eq.(16) $\phi_1 = \frac{\pi}{2}+\frac{1}{40}\pi$. 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.6a.

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 $x_S = 1$ during a interacting propagation distance equal to $z_S = 30$. Using eqs.(2-6) we obtain that the acceleration must be equal to $a_R = 2.2\cdot 10^{-3}$, 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 of these accelerations. Using eq.(16) we obtain $\phi_2 = \frac{\pi}{2}+\frac{2}{40}\pi$. 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 figs. 6.

In fig. 6b 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 in locked inside the waveguide as shown in fig.7a.

In fig. 6c 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 $\phi_1 = \frac{\pi}{2} + \frac{1}{40}\pi$ 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. 6d 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 $\phi_2 = \frac{\pi}{2} + \frac{2}{40}\pi$ 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.

8. A NUMERICAL DESIGN OF THE DEVICE

We want now to give a numerical example for the design of the considered device.

We suppose to have a Schott B 270 glass, whose optical parameters at $\lambda_0 = 620\text{nm}$ are $n_0 = 1.53$ and $n_2 = 3.4 \cdot 10^{-20}\,\text{m}^2/\text{W}$ being n_0 and n_2 are the linear and nonlinear refractive indices respectively[18]. Let us consider a spot size of the beam equal to $d_0 = 1\mu\text{m}$.

We have first to dimension the whole path of the loop according to the temporal interval between two subsequent pulses of the train. We suppose that it is equal to 5 ps. Therefore each of the 4 branches of the loop must be crossed in 1,25 ps, that corresponds to an extension of 375 μm.

The first parameter that we chose is 'a'. Suppose to select an initial value equal to $2 \cdot 10^{-4}$, we have to calculate the maximum length L of the parabolic waveguide that respect the paraxial condition expressed from eqs.(12)-(13) and (14). If L is longer than 375 μm, it is necessary to consider a shorter distance while if L is longer it is necessary to consider an extra path between the end of the parabolic waveguide and the mirror.

Substituting the chosen value of a= $2 \cdot 10^{-4}$ in eq.(13) we obtain L=350 μm. The correspondent transversal path can be calculated substituting the numerical values into eq.(14) that gives x_L =24.5.

Due to the low curvature of the considered parabolic waveguide, it is possible to approximate it with a straight line and to calculate its length as the hypotenuse of the rectangle triangle whose sides are L and x_L. Since L>> x_L, it is possible to see that the path is nearly equal to L.

To reach the total calculated length of the branch of the loop of 375 μm it is necessary consider an extra path of 25 μm between the end of the parabolic waveguide and the mirror. If this path is a straight line whose inclination with respect to the longitudinal axis is the one that assumes the parabolic waveguide, that is the maximum allowed from the paraxial approximation, equal to 8°, its projection on transversal and longitudinal axes is equal to 3.5 μm and 24.5 μm.

It is well known that, given a certain material and a certain light source, the intensity necessary to generate a soliton beam is given by:

$$I_s = \frac{2n_0}{d_0^2 n_2 \beta} \tag{17}$$

where β is the wavevector of the beam. Substituting the numerical values into eq.(17) we have $I_s = 3.74 \cdot 10^{17}\,W/m^2$.

Since the intensity of the beam I_s is related to its amplitude C from[14]:

$$I_s = \frac{1}{\left[\log\left(2+\sqrt{3}\right)\right]^2}\frac{n_0}{2n_2}C^2 , \tag{18}$$

it is possible to express eqs.(10) and (12) in term of the intensity of the beams.

We have now to choose the parameter b and Δn_0 according to the detach value of the intensity of the beam that we desire, that, according to our calculations, is equal to $I_s = 3.74 \cdot 10^{17} W/m^2$. This means that, if we inject a soliton beam inside this parabolic waveguide it is surely expelled at the end. Since we are in the presence of absorption, it is expelled before the end, that is what we want after that the addresser soliton has correctly switched the data soliton. The presence of absorption is anyway analysed later. If we choose for example $\Delta n_0 = 1 \cdot 10^{-2}$ and b=1.15, using L=350 μm, substituting the numerical values into eq.(10), using eq.(18) we obtain $I_D = 3.93 \cdot 10^{17}$ W/m^2, that is the soliton beam is locked up to the end of the waveguide in the absence of absorption.
In the presence of absorption, the amplitude is decreased during the propagation and the beam is expelled at a distance that is shorter than L. Since the addresser soliton has to propagate on the loop waveguide a number of times equal to the number of data solitons composing the data train, it is necessary to inject a soliton whose intensity is properly over dimensioned, depending on the value of the absorption coefficient of the material, remembering that its intensity has to be less than 4 times the intensity calculated with eq.(17) to avoid the generation of a second order soliton that would invalidate our results.

9. BEHAVIOUR OF THE LOOP WAVEGUIDE IN THE PRESENCE OF ABSORPTION

The question we want to solve now is the following: given a certain absorption of the material and a certain length of the loop, we ask what is the value of the intensity I_a of the addresser soliton or equally the value of n, where $I_a = \mathrm{n} I_s$, that allows a certain number of data pulses N_P to be switched towards the desired output. This is equal to express n as a function of N_P.
Given a certain material, it is also given the absorption coefficient A, expressed in dB/m. Suppose to have a certain loop waveguide, characterised by a total length equal to L_{TOT}, equipped with two mirrors, characterised by a well defined reflection coefficient A_M, expressed in dB. We suppose the coefficients of the attenuation to be expressed as positive numbers. The total absorption coefficient of the loop is:

$$A_L = AL_{TOT} + 2A_M . \tag{19}$$

The attenuation A_L is obviously expressed as a positive number.
The total attenuation, for a beam that propagates N_P times inside the loop, is:

$$A_{TOT} = N_P\left(AL_{TOT} + 2A_M\right) = 20\log_{10}\frac{I_a}{I_s} = 20\log_{10} \mathrm{n} , \tag{20}$$

that is a positive quantity too.
Eq.(20) can be solved with respect to n giving:

$$n = 10^{\frac{N_P\left(AL_{TOT}+2A_M\right)}{20}} . \tag{21}$$

Eq.(21) tells us what is the extra intensity that the addresser soliton must have with respect to the data soliton, to propagate, and therefore to switch, N_P times inside the loop. The minimum value of n is obviously 1, that is the absence of absorption, a situation that doesn't allow the expulsion of the addresser soliton. The maximum value of n is 4, that implies the generation of a second order soliton, practically unusable for our purpose. Eq.(20) is shown in fig.7 for different values of the attenuation of the material. The reflection coefficient of the single mirror has been chosen to be equal to 99.5%, that is equal to an attenuation of $4.35 \cdot 10^{-2}$ dB, that gives, for the two mirrors, an attenuation of $8.7 \cdot 10^{-2}$ dB.
In general we are interested to know the maximum number of pulses that it is possible to switch with a given structure for different materials with different coefficients of attenuation. The maximum number of propagations takes place when n=4. Substituting this value into eq.(20) and solving with respect to N_P we obtain:

$$N_P^{\max} = \frac{20\log_{10} 4}{\left(AL_{TOT} + 2A_M\right)}, \tag{22}$$

that expresses $N_P^{\max}$ as a function of A. Eq.(22) is shown in fig.8.
The number N_P can be properly increased by decreasing the denominator of eq.(22) that is by reducing the length of the loop, the coefficient of absorption of the material or increasing the reflectivity of the mirrors. The length of the loop L_{TOT} cannot be reduced under a certain limit that is imposed from the temporal interval between two subsequent pulses. The attenuation A_M of the mirrors can be reduced until reaching a reflectivity of the order of 99.95% but no more due to physical limitations, equal to an attenuation of $4.35 \cdot 10^{-2}$ dB. The attenuation A of the material can be reduced using a

medium that is well transparent at the used wavelength, but it is not necessary to reduce below a certain limit after which the attenuation of the mirror becomes dominant. In fact, using a loop that is 1.5mm long, as the one we have designed, the attenuation of the material begins to be comparable with the one of the two mirrors, equal to $8.7 \cdot 10^{-2}$ dB/m, for attenuation values of 60 dB/m, that gives an attenuation of the loop A $L_{TOT} = 9 \cdot 10^{-2}$ dB.

It is useful, at this point, to find the maximum value of the coefficient of absorption A_{1P} that the material can have, considering the structure of the loop waveguide, that doesn't allow the switching of almost a single pulse. This is equal to set N_P =1 in eq.(22) and to solve with respect to A:

$$A_{1P} = \frac{20 \log_{10} 4 - 2A_M}{L_{TOT}} . \tag{23}$$

Since the numerator of eq.(23) must be positive, we obtain a further condition for the mirrors:

$$A_M \leq 10 \log_{10} 4 , \tag{24}$$

representing the maximum value of the coefficient of attenuation of the mirrors that allows the device to switch almost one data pulse. Substituting the numerical values into eq.(23) we obtain, for the designed device, $A_{1P} = 8 \cdot 10^3$ dB/m

10. CONCLUSIONS

We have studied and designed an all optical router, whose working principles are based on the properties of soliton beams. In particular we used the property of repulsion between properly phased solitons and the property of propagation in a longitudinal parabolic waveguide, that we analysed in this paper.

The switching properties have been studied in details, obtaining some useful design criteria that help to project a practical device.

The router device can be properly designed by means of the width, the curvature and the refractive index of the loop waveguide, that compose the structure.

The operative frequency, that in the designed device is of the order of hundreds of Ghz, can be properly chosen by varying the length of the loop waveguide.

The number of outputs can be increased as desired since the switching between them is ensured by controlling the relative phase of the addressing soliton with respect to the data solitons. The increase of the outputs does not influence the operative frequency that remains relatively high.

11. REFERENCES

1. R. Y. Ciao, E. Garmire, and C. H. Townes, "Self-trapping of optical beams", *Phys. Rev. Lett.*, vol. 13, pp. 479-482, 1964.
2. B. Luther-Davies and Y. Xiaoping, "Waveguides and Y junctions formed in self-defocusing dark spatial soliton", *Opt. Lett.*, vol. 17, pp. 496-498, 1992; "Steerable optical waveguides formed in self-defocusing media by using dark spatial soliton", *Opt. Lett.*, vol. 17, pp. 1755-1757, 1992.
3. W. Krolikowski, and Y. S. Kivshar, "Soliton-based optical switching in waveguide arrays", *J. Opt. Soc. Am. B*, vol. 13, pp. 876-887, 1996.
4. N. N. Akhmediev, and A. Ankiewicz, "Spatial soliton X-junctions and couplers", *Opt. Comm.*, vol. 100, pp. 186-192, 1993.
5. W. Krolikowski, X. Yang, B. Luther-Davies, and J. Breslin, "Dark soliton steering in a saturable nonlinear medium", *Opt. Comm.*, vol. 105, pp. 219-225, 1994.
6. A. P. Sheppard, "Devices written by colliding spatial solitons: a coupled mode theory approach", *Opt. Comm.*, vol. 102, pp. 317-323, 1993.
7. J. P. Gordon, "Interaction forces among solitons in optical fibers", *Opt. Lett.*, vol. 8, pp. 596-598, 1983.
8. F. Garzia, C. Sibilia, M. Bertolotti, R. Horak, and J. Bajer, "Phase properties of a two-soliton system in a nonlinear planar waveguide", *Opt. Comm.*, vol. 108, pp. 47-54, 1994.
9. A .B. Aceves, J. V. Moloney, and A. C. Newell, "Reflection and transmission of self-focused channels at nonlinear dielectric interfaces", *Opt. Lett.*, vol. 13, pp. 1002-1004, 1988.
10. P. Varatharajah, A. B. Aceves, and J. V. Moloney, "All-optical spatial scanner", *App. Phys. Lett.*, vol. 54, pp. 2631-2633, 1989.
11. A .B. Aceves, P. Varatharajah, A. C. Newell, E. M. Wright, G. I. Stegman, D. R. Heatley, J. V. Moloney, and H. Adachihara, "Particle aspects of collimated light channel propagation at nonlinear interfaces and in waveguides", *J. Opt. Soc. Am. B*, vol. 7, pp. 963-974, 1990.

12. F. Garzia, C. Sibilia, and M. Bertolotti, "Swing effect of spatial soliton", *Opt. Comm.*, vol. 139, pp. 193-198,1997.
13. F. Garzia, C. Sibilia, and M. Bertolotti, "High pass soliton filter", *Opt. Comm.*, vol. 152, pp. 153-160, 1998.
14. F. Garzia, C. Sibilia, and M. Bertolotti, "All optical soliton based router", *Opt. Comm.*, vol. 168/1-4, pp. 277-285, 1999.
15. H. W. Chen, and T. Liu, "Nonlinear wave and soliton propagation in media with arbitrary inhomogeneities", *Phys. Fluids*, vol. 21, pp. 377-380, 1978.
16. P. K. Cow, N. L. Tsintsadze, and D. D. Tsakhaya, "Emission of ion-sound waves by a Langmuir soliton moving with acceleration", *Sov. Phys. JETP*, vol. 55, pp. 839- 843, 1982.
17. J. S. Aitchison, A. M. Weiner, Y. Silberberg, M. K. Oliver, J. L. Jackel, D. E. Leaird, E. M. Vogel, and P. W. E. Smith, "Observation of spatial optical solitons in a nonlinear glass waveguide", *Opt. Lett.*, vol. 15, pp. 471-473, 1990.