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All-optical soliton based router

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Abstract

A device able to address a train of equally spaced pulses between two or more outputs, according to the value of the relative phase of the first pulse with respect to the others, is presented. 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. © 1999 Published by Elsevier Science B.V. All rights reserved.

1. Introduction

Spatial solitons are self-trapped optical beams that are able to propagate without any change of their spatial shape, thanks to the balance between diffraction and nonlinear refraction in a self-focusing medium [1].

A number of spatial optical switches has been studied utilising the interaction between two bright or dark soliton beams, and the waveguide structures induced by these interactions [2–8]. Two distinct parallel solitons are generally used as initial conditions for such interactions. In fact, it is well known that when two distinct bright spatial solitons are launched parallel to each other, the interaction force between them depends on their relative distance and phase [9,10].

The useful properties of solitons enable a variety of useful devices to be designed. One of the most important features is their particle-like behaviour and their relative robustness to external disturbs. Interesting effects have been found in the study of transverse effects of soliton propagation at the interface between two nonlinear materials [11–13] or in a material in the presence of a Gaussian refractive index profile that is in the low perturbation regime [14].

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 capable of addressing a train of equally spaced pulses between two or more outputs, according to the value of the relative phase of the first pulse with respect to the others.

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

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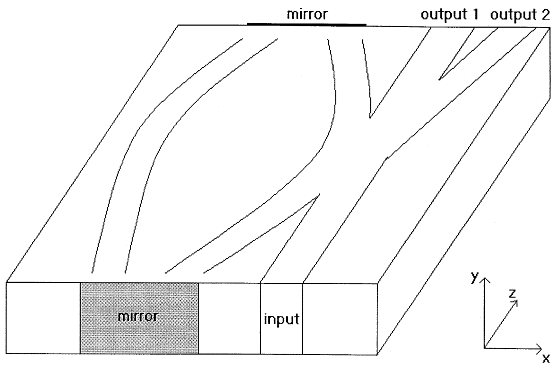

Fig. 1. Three-dimensional view of the structure of the considered device.

a triangular profile, whose longitudinal profile is parabolic, is studied. Once the properties of motion are derived, we investigate the structure from the global point of view, deriving all the properties and the operative conditions that represent the scope of this paper.

2. Structure of the router device

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 from the first pulse of the train, called addresser pulse, to realise an optical router. We propose working with soliton beams to use their attracting or repelling properties [9] and their particular behaviour when they propagate in a transverse refractive index profile [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 phase is chosen in a way that we explain later. The first pulse that enters the device is the addresser pulse. The loop waveguide is composed of two branches of a longitudinally parabolic waveguide and two mirrors. The behaviour of the parabolic waveguide is studied later. If the refractive index of the parabolic waveguide is a bit higher than that 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 the 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 tends to enter the loop waveguide: if we want it to propagate undisturbed to reach the first output, we have to introduce 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 output 2, it is necessary to produce an energetic 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 of 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 lowered so that it 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 now want to define the structure of the parabolic waveguide composing the loop to find its peculiar properties that allow the loop to work properly.

We chose this kind of waveguide because it is the simplest curve that progressively takes the soliton beam to the merging point of the waveguides and then again into the loop. This path could be roughly approximated to a linear and oblique curve, but the final result would be an overly sharp path that disturbs the repulsive effect that takes place into the merging point. Furthermore, 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:

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

where $\bar{x}$ is the position of the centre of the beam and C is a real constant on which both the width and the amplitude of the field depend. The variables x and z are normalised with respect to the wave vector 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 [15–17]:

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

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:

$$V_G = \frac{\mathrm{d}x_G(z)}{\mathrm{d}z} = 2az. \tag{4}$$

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

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

and the position of the beam

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

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 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 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:

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

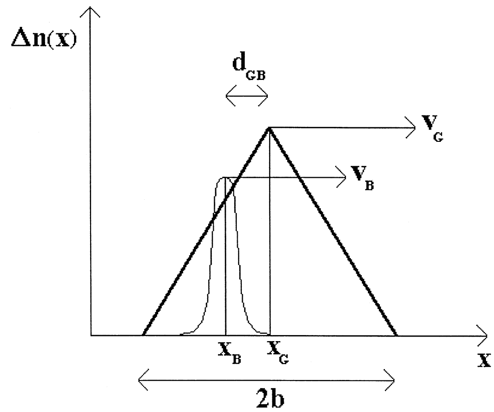

Fig. 2. Relative distance waveguide soliton at some propagation distance z.

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

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

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:

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

It is possible to see from Eq. (9) that the more the width of the profile (b parameter) increases or the curvature of the waveguide (a parameter) increases or the more the refractive index decreases, the more C_{D} increases. This behaviour agrees with what could be expected.

We now want 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:

$$\Phi = \tan^{-1} v_{\mathrm{D}} \tag{11a}$$

and

$$v_{\mathrm{D}} - v_{\mathrm{B}}(z_{\mathrm{D}}) = \frac{2\Delta n_o C^2}{\left(ab - \Delta n_0 C^2\right)^{1/2}}. \tag{11b}$$

Fig. 3 shows the graphical behaviour of Eqs. (11a) and (11b) for $a = 1 \times 10^{-3}$, $b = 4$, $\Delta n_0 = 1 \times 10^{-3}$. The detach value C_{D} can be calculated by Eq. (10) and is equal to 2.

Owing to the absence of restrictions about the length L of the waveguide, the lock-in value C_{D} of the amplitude, expressed from Eq. (10) does not depend on L. This means that, given a certain waveguide whose length is equal to L, we can obtain a lock-in value C_{D} whose detachment distance calculated from Eq. (9) is longer than L. In this situation, due to the restriction imposed from the waveguide length L, the detach value C_{D} obviously decreases. In fact, even if the beams characterised from an amplitude smaller than C_{D} tend to be expelled from the waveguide, the detachment takes place at a distance that is longer than the waveguide length L and the beam remains locked-in. The new value $C_{\mathrm{D}L}$, which is lower than C_{D}, can be calculated from Eq. (9) setting $z_{\mathrm{D}} = L$ and solving respect to C:

$$C_{\mathrm{D}L} = \frac{1}{L}\left[\frac{b}{\Delta n_0}(aL^2 - b)\right]^{\frac{1}{2}}. \tag{12}$$

Eq. (12) gives a further condition, through the length L, to obtain a solution for the detach amplitude that is:

$$L \geq \left(\frac{b}{a}\right)^{1/2}. \tag{13}$$

Since we are dealing 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

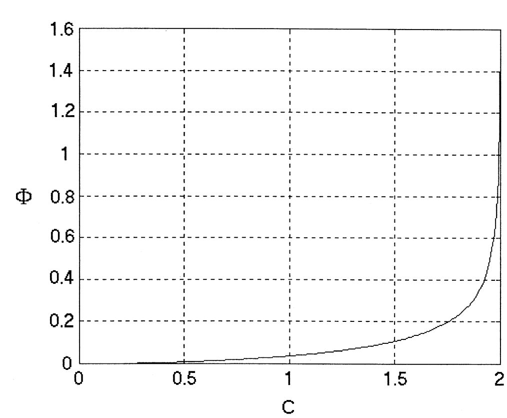

Fig. 3. Detach angle Φ in degrees, equal to atan(v_{D}), versus C for $a = 10^{-3}$, $b = 4$, $\Delta n_0 = 1 \cdot 10^{-3}$. The detach value is $C_{\mathrm{D}} = 2$.

the derived equations are valid until the angle between the propagation direction and the longitudinal direction is smaller 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, this means that it is possible to impose this condition on the first derivative of Eq. (3) to calculate the maximum propagation distance:

$$x'_G(z_{max}) = \tan 8° = 0.14 = 2az_{max} \quad (14)$$

that can be solved respect to z_{max}, giving:

$$z_{max} = \frac{7\times10^{-2}}{a}. \quad (15)$$

Substituting Eq. (15) into Eq. (3), it is possible to calculate the correspondening x_{max}:

$$x_{max} = \frac{4.9\times10^{-3}}{a}. \quad (16)$$

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.

4. Numerical simulation of the effect

We 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 amplitude of the soliton beam is $C=2$, while the parameters of the waveguide are $\Delta n_0 = 2\times10^{-3}$, $b=0.3$, $a=1.5\times10^{-4}$, which gives a detach value $C_D=2$. The refractive index of the loop waveguide is 10% higher than the refractive index of the main waveguide. The results are shown in Fig. 4.

In Fig. 4(b), 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 $C_D=2$ ($C=2.5$ in the simulation). In this case, the beam in locked inside the waveguide, as shown in Fig. 4(a).

In Fig. 4(c), the commutation on the main waveguide (output 1), operated from the addresser soliton with respect to the data soliton, is shown. In this case, given a certain refractive index difference between the two waveguides, it is necessary to find the relative phase value that allows the addresser soliton to repel the data soliton, by means of numerical simulations, in a way that it propagates just undisturbed on its original trajectory, remaining in the main waveguide and reaching the output 1. Starting from a neutral condition, that is there is no attraction or repulsion between the two beams [9], corresponding to a relative phase equal to $\pi/2$, the first useful found value is $6\pi/10$. In this situation, the data soliton is switched on the output 1 as required, while the addresser soliton remains locked inside the loop waveguide.

In Fig. 4(d), the commutation on the secondary waveguide (output 2), operated from the addresser soliton with respect to the data soliton, is shown. In this case, the relative phase has been chosen to be equal to π, to ensure the maximum repulsion of the data soliton that is addressed towards the output 2, while the addresser soliton remains locked inside the loop waveguide.

5. A numerical design of a router device

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

We assume we have a Schott B 270 glass, whose optical parameters at $\lambda_0 = 620$ nm are $n_0 = 1.53$ and $n_2 = 3.4\times10^{-20}$ m^2/W, where 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 $d_0 = 1$ μm.

We first have to dimension the whole path of the loop according to the temporal interval between two subsequent pulses of the train. We assume that it is

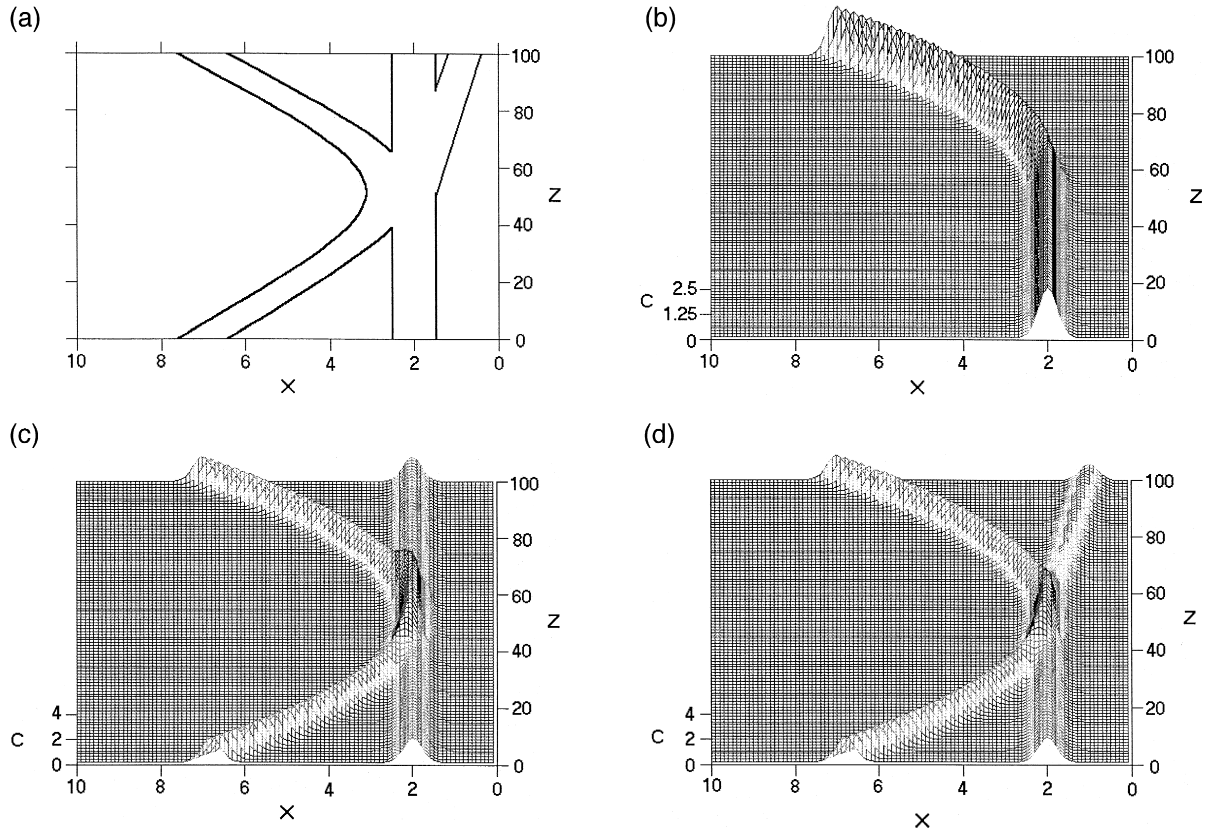

Fig. 4. Upper view of the structure and numerical simulations. The parameters of the waveguide are $\Delta n_0 = 1.5 \times 10^{-4}$, $b = 0.3$, $a = 2 \times 10^{-3}$. The detach value of the loop waveguide is $C_D = 2$: (a) upper view of the structure; (b) numerical simulation of the entrance, inside the loop waveguide, of the addresser soliton; (c) numerical simulation of the commutation on the main waveguide (output 1), operated from the addresser soliton with respect to the data soliton, where the relative phase difference between the two solitons is $6\pi/10$; and (d) numerical simulation of the commutation on the secondary waveguide (output 2), operated from the addresser soliton with respect to the data soliton, where the relative phase difference between the two solitons is π.

equal to 5 ps. Therefore, each of the 4 branches of the loop must be crossed in 1.25 ps, which corresponds to an extension of 375 μm.

The first parameter that we chose is a. Suppose the to select an initial value equal to 2×10^{-4}, we have to calculate the maximum length L of the parabolic waveguide that respects the paraxial condition expressed from Eqs. (14)–(16). If L is more 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 $a = 2 \times 10^{-4}$ into Eq. (15), we obtain $L = 350$ μm. The corresponding transversal path can be calculated by substituting the numerical values into Eq. (16), which gives $x_L = 24.5$.

Owing 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 a right angled triangle whose sides are L and x_L. Since $L \gg x_L$, 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.

The structure of the calculated loop is shown in Fig. 5.

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:

$$I_s = \frac{2 n_0}{d_0^2 n_2 \beta}, \quad (17)$$

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

Since the intensity of the beam I_s is related to its amplitude C from Ref. [15]:

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

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

We now have to choose the parameter b and Δn_0 according to the detach value of the intensity of the beam that we require, which, according to our calculations, is equal to $I_s = 3.74 \times 10^{17}$ 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, which is what we want after the addresser soliton has correctly switched the data soliton. The presence of absorption is anyway analysed later. If we choose for example $\Delta n_0 = 1 \times 10^{-2}$ and $b = 1.15$, using $L = 350$ μm, substituting the numerical values into Eqs. (10), (11a), (11b) and (12), using Eq. (18) we obtain $I_D = 3.93 \times 10^{17}$ W/m^2 and $I_{DL} = 3.74 \times 10^{17}$ W/m^2. This means that, owing to the length L of the waveguide, the expulsion takes place at a lower intensity level I_{DL} respect to the value I_D calculated without restrictions. The result we obtain is that the soliton beam is expelled at the end of the waveguide in the absence of absorption.

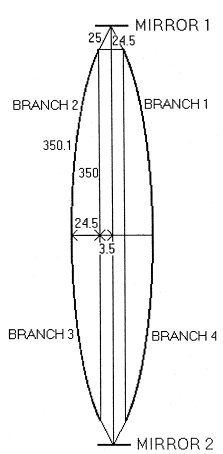

Fig. 5. Structure of the designed loop. The distances are only schematic since they are not in scale and are expressed in μm.

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.

6. 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 $I_a = n I_s$, that allows a certain number of data pulses N_P to be switched towards the desired output. This is equvalent to expressing n as a function of N_P.

Given a certain material, it is also given the absorption coefficient A, expressed in dB/m. Suppose we 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 assume the coefficients of the attenuation to be expressed as positive numbers. The total absorption coefficient of the loop is:

$$A_L = A L_{TOT} + 21 A_M. \quad (19)$$

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:

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

which is also a positive quantity.

Eq. (20) can be solved with respect to n, giving:

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

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 does not allow the expulsion of the addresser soliton. The maximum value of n is 4, which implies the generation of a second order soliton, practically unusable for our purpose. Eq. (20) is shown in Fig. 6 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%, which is equal to an attenuation of 4.35×10^{-2} dB, that gives for the two mirrors an attenuation of 8.7×10^{-2} dB.

In general, we are interested in knowing the maximum number of pulses that it is possible to switch

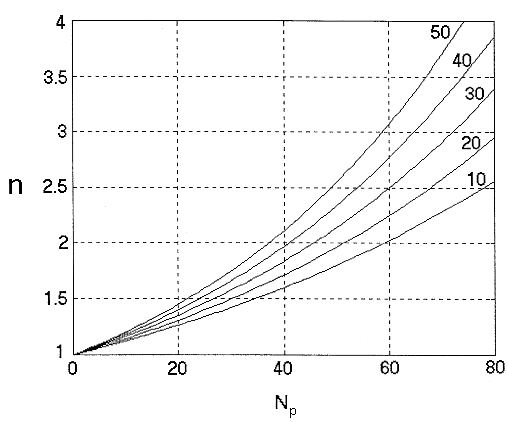

Fig. 6. Magnifying factor n of the intensity of the addresser soliton I_a, with respect to the intensity of the data soliton I_s, versus the number of data pulses of the train for different values of coefficient of attenuation A of the material, expressed in dB/m.

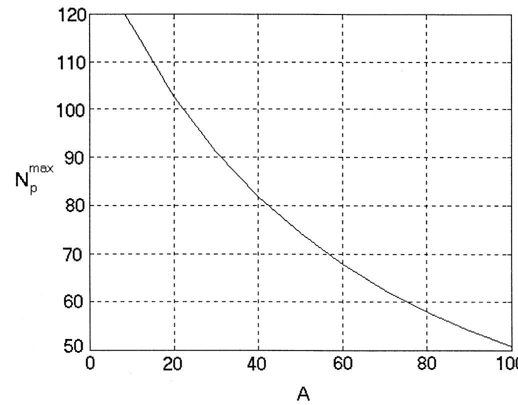

Fig. 7. Maximum number of data pulses of the train versus the coefficient of attenuation A of the material, expressed in dB/m.

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:

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

that expresses N_P^{max} as a function of A. Eq. (22) is shown in Fig. 7.

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 4.35×10^{-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 1.5 mm long, like the one we have designed, the attenuation of the material begins to be comparable with the one of the two mirrors, equal to 8.7×10^{-2} dB/m, for attenuation values of 60 dB/m, which gives an attenuation of the loop $A\,L_{TOT} = 9 \times 10^{-2}$ 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 does not 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:

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

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

$$A_M \leq 10\log_{10}4, \qquad (24)$$

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, $A_{1P} = 8 \times 10^3$ dB/m.

7. 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 detail, 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, which 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 required, 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, which remains relatively high.

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