All optical cryptographic device for security applications

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ABSTRACT

We present an all-optical cryptographic device for security applications, based on the properties of soliton beams. It is able to codify a given bit stream of optical pulses, inverting at will their order, to make the stream not understandable. Its great advance is represented by its capability of encrypting in real time, without slowing the data flow that can be transmitted with its original velocity.

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

1. INTRODUCTION

The continuous increasing of telecommunications also needs an increase of the security of carried data, that is to ensure their readability only to the final destination. This can be achieved by properly encrypting the data flow.

A cryptographic operation generally needs a certain time to be executed since it has to change in some way the natural meaning of the data using a proper cryptographic key, that is also used by the final destination to reconstruct correctly the original message.

To design an all optical device it is necessary to use proper switching effects such the one offered by spatial soliton. The interesting effects of soliton propagation at the interface between two nonlinear materials[1–3] or in a material in the presence of a gaussian refractive index profile, that is in low perturbation regime[4,5] demonstrate 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 particular it is possible to select the intensity level that a soliton beam must have to be trapped inside a curved waveguide[6] and to be propagated until a certain position, and the relative acceleration between two solitons when they interact partially overlapped[7].

In this paper we use the two mentioned properties to design an all optical device that acts as a cryptographic device that is able to codify a given bit stream of optical pulses, inverting at will their order, to make the stream not understandable.

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, whose properties have already been described[5-8].

We first illustrate the general structure of the device then we design the proposed device and finally test it by means of numerical simulations. Further we define some parameters that are very useful to derive the properties of the cryptographic device.

2. STRUCTURE OF THE CRYPTOGRAPHIC DEVICE

The device is composed by N equal elementary looped cells, where N is the number of pulses that compose the bit stream, whose maximum number is limited by some parameters that we will show in the following.

In the following we will also use the term bit to indicate the binary information carried by a particular pulse. In fig. 1 a two bit device is shown. The bit stream is supposed to be phase modulated and the binary information is coded by means of two phase conditions that do not differ more than $\pi/2$. In this way a bit pulse is always present in the data flow.

Let’s consider a N bit stream to be encrypted by the device. The first pulse enters the device and it is attracted by the first loop whose structure is studied to give to the soliton pulse, after a round trip inside it, a repulsive relative phase when it

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interacts with the following pulses of the querying code. Thank to this property the subsequent pulses are kept on the main waveguide reaching the following stages of the device, where the process repeats again. Since the data stream is characterised by phase modulated pulses whose relative phase do not differ more than $\pi/2$, it is always possible to choose a third phase value that result to be repulsive for both of them.

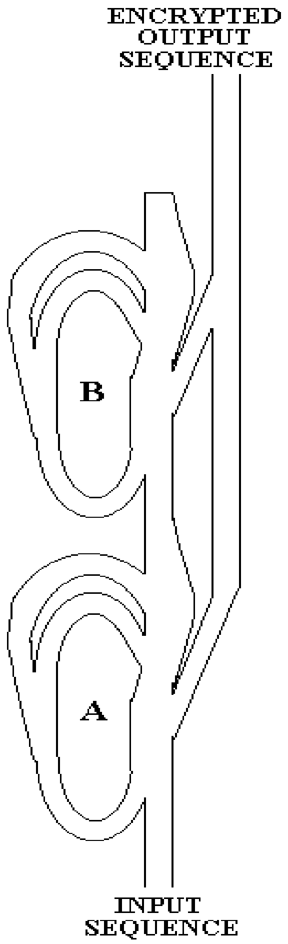

Fig.1 Scheme of a two bits cryptographic device.

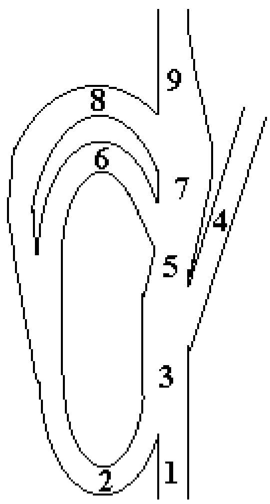

Fig.2 Scheme of an elementary loop cell. The guides 1, 3, 4, 5, 6, 7, 9 have the same refractive index while guide 8 has a higher refractive index with respect to the others.

Since the pulse are trapped inside the loop until their intensity is above a certain threshold, as we shall demonstrate in the following, once all the querying pulses have entered the device, they surely experience a certain attenuation due to absorption, decreasing their intensity in a different way according to the number of times that they have propagated inside the loops: this means that it is possible to choose for each of them how long it is locked inside its loop, shuffling at will the original sequence of the bit stream according to the desired order, encrypting it in real time.

We want now to describe into details the structure of the elementary loop cell that composes the device, whose scheme is shown in fig. 2. Since it is necessary to change the relative phase of the pulse that propagates inside the loop only once, to make it repels with the following pulses, a double branched loop is used. The first pulse enters the waveguide 1 and propagates through the waveguide 3, passing the waveguide 4 and the branch 6 of the loop, since they are both characterised by the same refractive index of the main waveguide and therefore the pulse is not attracted inside them. Since the branch 8 of the loop is characterised by a higher refractive index, the pulse is attracted inside it. The length of this branch is calculated so that the pulse experiences a phase variation that makes the soliton to repel the other pulses.

The soliton pulse propagates inside the loop until reaching again the point 3 where it propagates parallel with respect to the following pulse, and slightly overlapped to it so that a mutual repulsive force develops. They reach the point 5 where the waveguide becomes narrower and the mutual repulsive force greatly increases, pushing the first pulse into the branch 6 of

the loop and the second pulse towards the right hand side of the point 7 of the waveguide, where it becomes wider. In this situation the second pulse is far enough from the branch 8 of the loop to be attracted inside it, and it can reach the point 9 of the waveguide where it exits, reaching the following stage.
The first pulse propagates now into the shorter loop, whose length is calculated to let it have the same repulsive phase with respect to the other pulses after each trip, repeating the same process.
When all the pulses of the stream have entered the device the first pulse continues to propagate inside the loop decreasing its intensity because of the absorption until reaching a certain threshold, that depends on the properties of the loop, where the beam cannot be locked inside the loop waveguide, leaving it and reaching the waveguide 4 that takes it in the output code waveguide.
Designing the properties of each loop waveguide it is possible to fix the propagation time of each pulse inside it and therefore the position of the pulse in the output sequence that result to be encrypted with respect to the input sequence.

3. PROPAGATION PROPERTIES OF SOLITON IN THE CONSIDERED STRUCTURE

The loop structure is composed by longitudinal parabolic paths whose transverse refractive index profile follows a triangular distribution[5]. We choose this kind of waveguide because it is the simplest curve that takes progressively the soliton beam to the interaction point of the waveguides and then again into the loop. 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[6]. The local inclination of this longitudinally parabolic waveguide with respect to the longitudinal axes increases with propagation distance: this means that it is necessary to impose some limits to avoid of overcoming the paraxial approximation, endangering the validity of the Nonlinear Schroedinger equation (NLSE) and therefore of the whole theory we are developing. For this reason two mirrors are used to close the loop[6,7].
A soliton beam propagating in the z-direction, is characterised by the following expression of the field Q at the beginning of the structure:

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

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[5,9,10]. 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 chosen to be parabolic is characterised by the following expression:

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

where 'a' is a real constant responsible for the curvature of the waveguide.
In this situation it is possible to demonstrate that the beam remains trapped inside this waveguide if its amplitude is greater than:

$$C_D = \left(\frac{ab}{\Delta n_0}\right)^{1/2}. \tag{3}$$

Since we use to curves whose expression is given by eq.(2), with different values of 'a', to generate a proper difference of relative phase, it is necessary to find their length, and therefore their optical paths that induce the phase variation.
Considering eq.(2), the first derivative of z with respect to x is:

$$\frac{dz}{dx} = \frac{1}{2\sqrt{ax}} \tag{4}$$

and the elementary length of the curve, as a function of x is:

$$dl = \sqrt{dx^2 + dz^2} = \sqrt{dx^2 + \frac{1}{4ax}dx^2}. \tag{5}$$

Integrating eq.(5) we have:

$$L(x,a) = \frac{x}{2}\sqrt{\frac{1+4ax}{ax}} + \frac{1}{8a}\log\left(1 + 8ax + 4ax\sqrt{\frac{1+4ax}{ax}}\right) + \text{constant}. \tag{6}$$

The constant in eq.(6) can be determined calculating the limit of the integral when x tends to zero:

$$\lim_{x \to 0} L(x) = 0 . \tag{7}$$

that is the constant is equal to zero.
The length of the curve L(x,a) is therefore equal to:

$$L(x,a) = \frac{x}{2}\sqrt{\frac{1+4ax}{ax}} + \frac{1}{8a}\log\left(1 + 8ax + 4ax\sqrt{\frac{1+4ax}{ax}}\right), \tag{8}$$

that is obviously a function of ‘a’ and x.

4. INTERACTION BETWEEN SOLITON BEAMS

To let our device to work properly we use the interaction force between solitons whose expression has been demonstrated to be an exponential function of the relative distance d and a cosinusoidal function of the relative phase ϕ, according to the following equation[7]:

$$a(d,\varphi) = \frac{C^2}{5}\exp(-C(d - 2x_{HHHW}))\cos\phi , \qquad (d \geq 2x_{HHHW}) \tag{9}$$

where x_{HHHW} is the half height half width that is the distance from the centre of the beam where the amplitude reduces to one half, equal to:

$$x_{HHHW} = \frac{1}{C}\log\left(2 + \sqrt{3}\right), \tag{10}$$

The expression (9) is very useful in the quantification of the mutual acceleration between solitons and it is used to design the device.

5. DESIGN OF THE DEVICE

We start by designing the parabolic waveguide. We choose for the main loop a refractive index Δn_0 equal to 10^{-3}. If we also choose b=1 and a= $4 \cdot 10^{-4}$ we can calculate from eq.(4) the lock-in value for the amplitude that is about 0.4. We decide to use, for our device, a value for the amplitude C equal to 2. Once chosen the main loop, since we are free to decide the temporal length of the pulses, it is necessary to define its maximum length. We use as limit the paraxial approximation, that imposes the curve do not exceed a curvature of about 8°-10° with respect to the longitudinal axes. It is immediate to verify that if we let the curve to extend up to a transversal distance equal to 10, that is a longitudinal distance equal to 150, this approximation is respected.
We have now to define the external half-loop that is the loop where the beam propagates only the first time to acquire a repulsive relative phase difference. The transversal length of this curve is imposed by the internal loop and its total length can be calculated using eq.(8), as a function of the ‘a’ parameter. The difference between the total length of the external curve, that is a function of the ‘a’ parameter, and the total length of the internal curve multiplied by two gives the difference of path between the two curves. Since we deal with normalised wavevectors and refractive index, this difference is also equal to the phase difference. Since the phase is periodical, it is possible to choose different values for the ‘a’ parameter of the curve, without taking care of the paraxial approximation, that is surely respected since this half-loop is less curved with respect to the internal loop that already respects this condition. The only restriction is obviously the total length of the structure that we want to be as short as possible. The research of this ‘a’ value can be made solving numerically the expression that gives the phase difference as a function of the length of the curves expressed by means of eq.(8), due to the complexity of its form. A repulsive phase difference is attained if we chose for the external loop a= $1.99 \cdot 10^{-4}$. In this case the transversal extension of this curve is equal to 10, since we have imposed it for analogy with the internal loop, while its longitudinal distance is equal to 220, that is obviously a higher value with respect to the internal loop.
We have finally to choose a higher value for the refractive index Δn_0 with respect to the internal loop and to the main waveguide, so that the half-loop is able to attract and capture the soliton beams that propagates close to its entrance. If we chose, for example, $\Delta n_0 = 1.5 \cdot 10^{-3}$, we attain this effect and it is immediate possible to demonstrate, by means of eq.(3) that the lock-in value for the amplitude for this half-loop is about equal to 0.36, that is 10% less than lock-in value for the internal value. This ensures that, if a soliton beam is trapped inside the internal loop it is surely trapped inside the external loop. Since we have chosen C=2, the beams we are considering are surely trapped by both loops.

We have designed, until this point, the loop structure of the device. It is now necessary to design the structure of the main waveguide. We chose the same refractive index with respect to the internal loop, that is $\Delta n_0 = 1 \cdot 10^{-3}$, so that the beams that propagates inside it tends to remain there until their intensity decreases under the threshold, so that they are expelled towards the output waveguide. The value chosen is $\Delta n_0 = 1.1 \cdot 10^{-3}$.
The expression of the transversal acceleration of a soliton beam in a linear transversal refractive index profile is equal to[6]:

$$a_T = \frac{2\Delta n_0}{b} C^2 \tag{11}$$

When the beam propagates from loop 2 to the zone 3 of the waveguide it is subjected to a force that tends to attract it inside the loop and a force that tends to attract it inside the main waveguide, in an opposite direction. Since the refractive index of the main waveguide is a bit higher with respect to the loop, the beam tends to move slowly towards it with an acceleration that can be calculated from eq.(11), where Δn_0 is the difference between the two refractive index. Substituting the numerical values we have $a_T = 8 \cdot 10^{-4}$. Since the transversal co-ordinate of the beam x_B is related to its longitudinal co-ordinate from:

$$x_B = \frac{1}{2} a_T z^2 , \tag{12}$$

it is possible to express eq.(12) as a function of z variable giving:

$$z = \sqrt{\frac{2x_B}{a_T}} . \tag{13}$$

Since the transversal distance from one side to the other of the main waveguide is equal to 2, substituting the numerical values into eq.(13) we obtain that z=70, that is the longitudinal distance between the exit of the loop 3 and the entrance of the waveguide 4.
Since the beam is attracted out of the loop from an acceleration equal to $a_T = 8 \cdot 10^{-4}$, it is possible to determine the relative distance, between two solitons inside the zone 3 of the waveguide, that generates a repulsive force exactly equal to the transverse force generated by the index profile. Using eq.(9) we have d=4.4, that is the maximum distance above which the repulsive force is no more able to balance the attraction force. Using a shorter distance we are sure that not only the attraction force is compensated but that one soliton is also pushed inside the loop 6.
The narrowed zone 5 is positioned immediately after the waveguide 4 so that the repulsion of the second soliton towards the right hand side of the waveguide does not push it out through the waveguide 4. In this way the second soliton propagates far enough from the loop 8 to be attracted from it, while the first soliton is pushed inside loop 6 by the repulsive action between the two solitons.

6. NUMERICAL SIMULATION OF THE DEVICE

The designed device has been numerically simulated using a FD-BPM algorithm, to check the validity of the developed theory.
The structure of the waveguides that compose the device are shown in fig.3a.
We do no consider the left side of the loop waveguides since the most significant interaction effects take place in the merging point of the different waveguides, situated on the right hand side of the structure.
In fig.3b it is considered the entrance of the first soliton inside the outer loop. In fig.3c it is considered the switching operated from the first soliton with respect to the other solitons. In fig.3d it is considered the propagation inside the loop of the first soliton in the absence of other soliton. In fig.3e it is considered the exit of the first soliton from the loop 3 due to its below-threshold amplitude. The numerical simulations confirm the correct behaviour of the designed device.

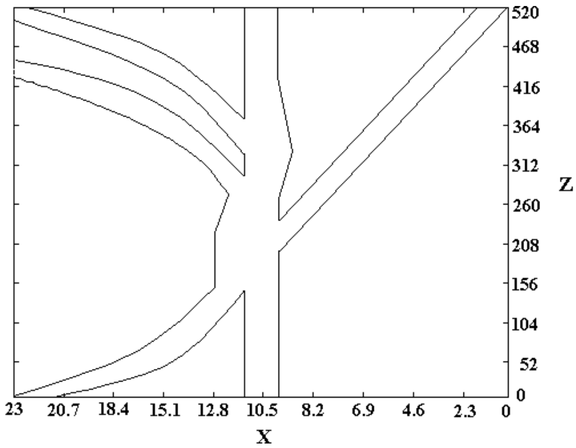

Fig.3(a) Upper view of the structure.

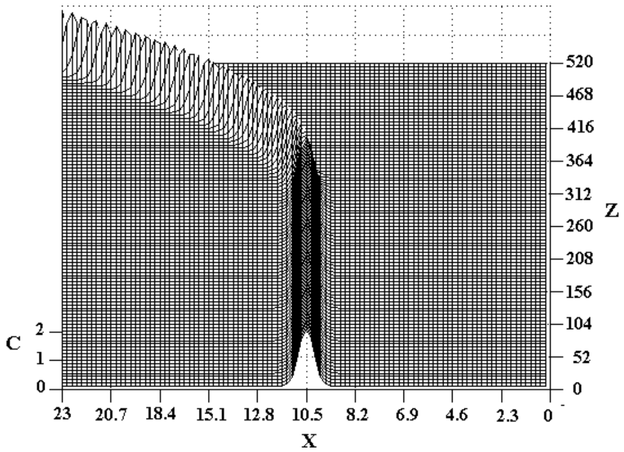

Fig.3(b)

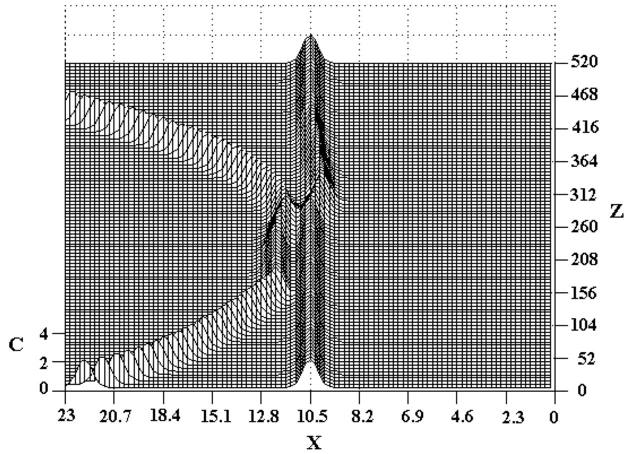

Fig.3(c)

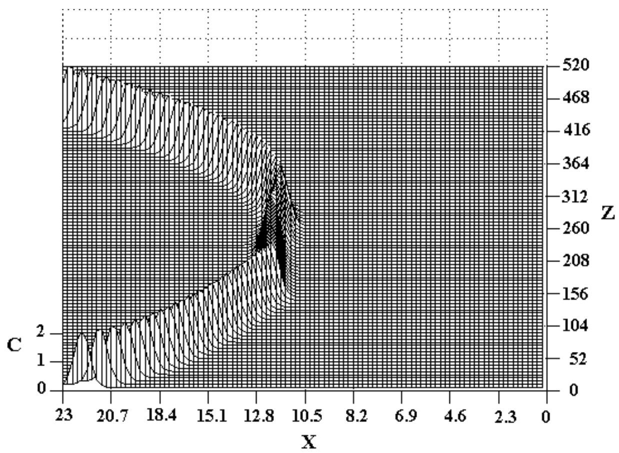

Fig.3(d)

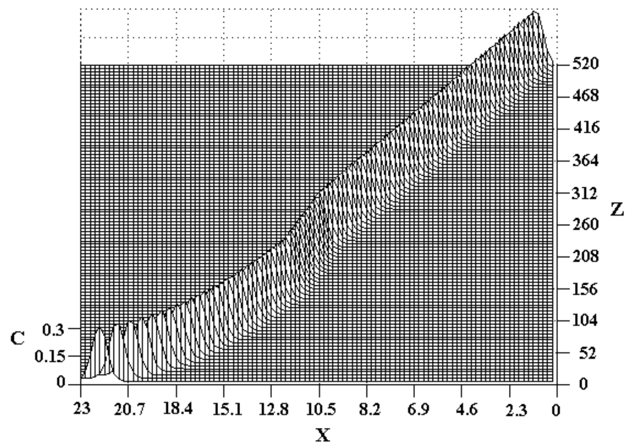

Fig.3(e)

Figs.3: (b) Numerical simulation of the entrance of the first soliton inside the half-loop.
(c) Numerical simulation of the switching operated from the first soliton with respect to the other solitons.
(d) Numerical simulation of the propagation of the first soliton inside the loop waveguide in the absence of other solitons. Its amplitude is above the threshold of the loop that is equal to 0.4.
(e) Numerical simulation of the exit of the first soliton from the loop waveguide to reach the output waveguides. Its amplitude is below the threshold of the loop that is equal to 0.4.

7. OPERATIVE PARAMETERS OF THE DEVICE

We have neglected, until this point, the absorption of the material whose effect consists in reducing the intensity of the beams until reaching the threshold under which they are no more trapped inside the loops, altering the output sequence with respect to the input sequence.
The worst situation takes place when the cryptographic sequence is chosen so that the first pulse of the input sequence must be the last pulse of the output sequence: in this situation the pulse must propagates 2N times inside the loop, where N represents the number of pulses that compose the sequence to be encrypted.
If I_P is the intensity of the pulse soliton and I_L is the lock-in intensity of the considered loop waveguide with respect to intensity of the base soliton, it is obvious that $I_P > I_L$ to let the soliton propagate inside the waveguide a certain number of time. If we set $I_P = n I_L$, it is possible to express the ratio n between the two considered intensities to the absorption of the loop and to the number of times N_P that we want the pulse to propagate inside it, that depends on the chosen cryptographic sequence: each pulse is characterised by a different number of round trips inside its loop to be repositioned in the output sequence.
The absorption of the loop depends on its geometry and on the used material. In particular the length of the loop depends on the temporal length of the pulses. In fact the more the pulses are longer and the more it is necessary to increase the length of the loop to let the pulses have the same phase after one trip inside the loop. This means that the absorption of the loop increases with the length of the pulse. To find an analytical expression of this relation it is necessary to know the absorption coefficient A, expressed in dB/m.
The loop waveguide, is characterised by a total length L_{TOT}, and by two mirrors, characterised by a well defined reflection coefficient A_M, expressed in dB. We suppose the attenuation coefficients to be expressed as positive numbers. The length of the loop L_{TOT} can be expressed as a function of the length of the pulses τ as:

$$L_{TOT} = \frac{c}{n_0}\tau \, , \tag{14}$$

where c is the velocity of the light in the vacuum and n_0 the refractive index.
The total absorption coefficient of the loop is:

$$A_L = AL_{TOT} + 2A_M \, . \tag{15}$$

The total attenuation, for a beam that propagates N_P times inside the loop, is:

$$A_{TOT} = 20\log_{10}\frac{I_P}{I_L} = 20\log_{10} \mathrm{n} = N_P\left(AL_{TOT} + 2A_M\right) = N_P\left(A\frac{c}{n_0}\tau + 2A_M\right), \tag{16}$$

that is a positive quantity.
Eq.(16) can be solved with respect to n giving:

$$n = 10^{\frac{N_P\left(A\frac{c}{n_0}\tau + 2A_M\right)}{20}} \, . \tag{17}$$

Eq.(17) expresses the ratio n of the intensity I_P of the soliton pulses with respect to the lock-in intensity I_L of the loop as a function of the number of times N_P that the pulse must propagate inside the loop.
Once the features of the input pulses (I_P, τ), of the used material (A), and of the used mirrors (A_M) are known, and the geometry of the loop ('a' and b) and the position of the pulse in the output sequence (N_P) are established, it is possible to calculate the parameter n using eq.(17), that is the lock-in intensity I_L of the loop waveguide.
For a soliton beam its amplitude C is linked to its intensity I by[4,5]:

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

where n_0 is the linear refractive index of the material and n_2 is the nonlinear refractive index of the material.
Substituting eq.(3) into eq.(18), remembering that the detach amplitude C_D is directly related to the lock-in intensity I_L, solving with respect to Δn_0 we have:

$$\Delta n_0 = \frac{n_0 ab}{2n_2\left[\log(2+\sqrt{3})\right]^2 I_L} \qquad (19)$$

that is the refractive index of the loop waveguide is related the lock-in intensity of the waveguide. Remembering that I_P=nI_L, using eqs.(17) and (19) we have:

$$\Delta n_0 = \frac{n_0 ab}{2n_2\left[\log(2+\sqrt{3})\right]^2 I_P} 10^{\frac{N_P\left(A\frac{c}{n_0}\tau+2A_M\right)}{20}} \qquad (20)$$

that is the refractive index of the loop as a function the number of times N_P that the pulse must propagate inside it to change its position in the output sequence. This means that the geometry is the same for all the loops while the refractive index Δn_0 of each of them is different and depends on the different position of the pulse in the output sequence with respect to the input sequence, that depend on the chosen cryptographic key. The cryptographic key gives the value of N_P for each loop.

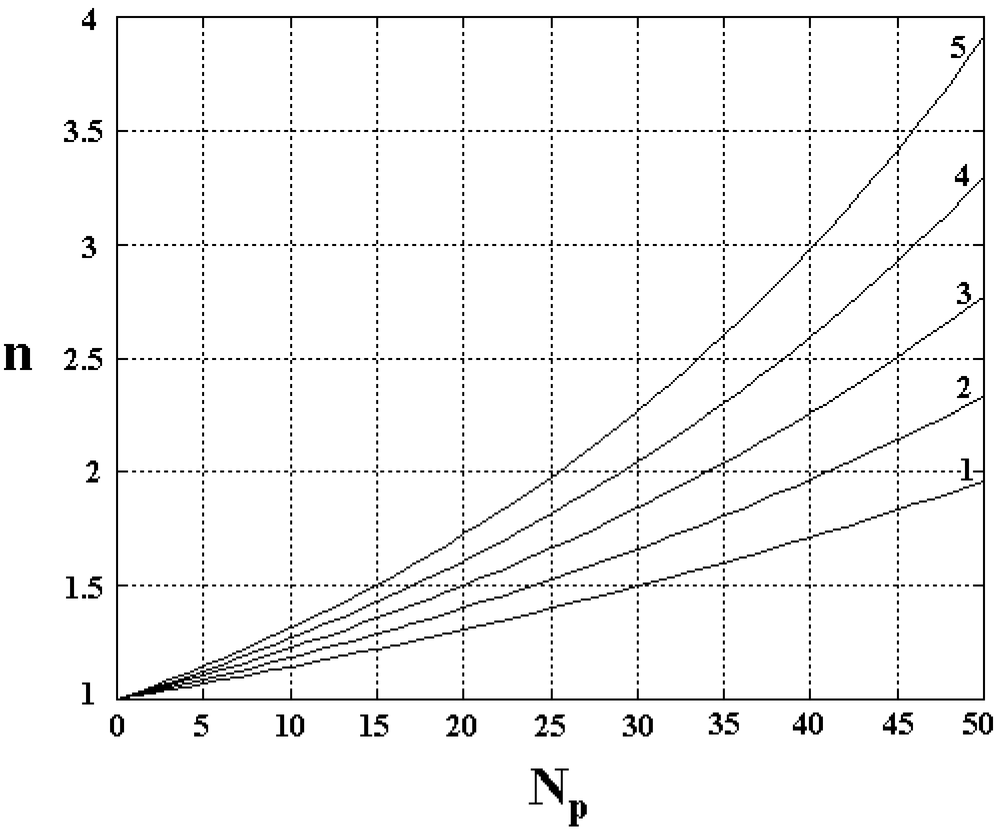

Fig.4 Factor n versus the number of times N_P that the pulse must propagates inside the loop for different values of the temporal length τ of the pulse, expressed in picoseconds. The absorption coefficient A of the material is equal to 150 dB/m.

The value of n given by eq.(17) cannot have any value. In fact there is a lower limit given by the soliton generation threshold I_S [4,5] under which the intensity of the pulse is no more able to generate a soliton beam inside the loop, and an upper limit given by the second order generation threshold that is equal to 4 times the lower threshold. This means that if we choose for the loop waveguide $I_L = I_S$, I_P cannot exceed 4 times I_L, that imposes n<4 and put a limit to the maximum number of times N_P that the pulse can propagate inside the loop. Eq.(17) is shown in fig.4 as a function of N_P, where 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.
Since we are interested to know the maximum number of bits of the input stream that the device can handle, we want to find the theoretical limit.
We already said that the worst situation takes place when the cryptographic sequence is chosen so that the first pulse of the input sequence must be the last pulse of the output sequence: in this situation the pulse must propagate 2N times inside the loop, where N represents the number of pulses that compose the sequence to be encrypted.
The maximum number of pulses N_P =2N can be obtained when the scale factor n is equal to 4. Substituting this value into eq.(16) and solving with respect to N_P we obtain:

$$N_P^{\max} = \frac{20\log_{10} 4}{\left(A\dfrac{c}{n_0}\tau + 2A_M \right)}, \qquad (21)$$

that expresses $N_p^{\max}$ as a function of the attenuation A of the material and the length τ of the pulses. Eq.(21) is shown in fig.5.

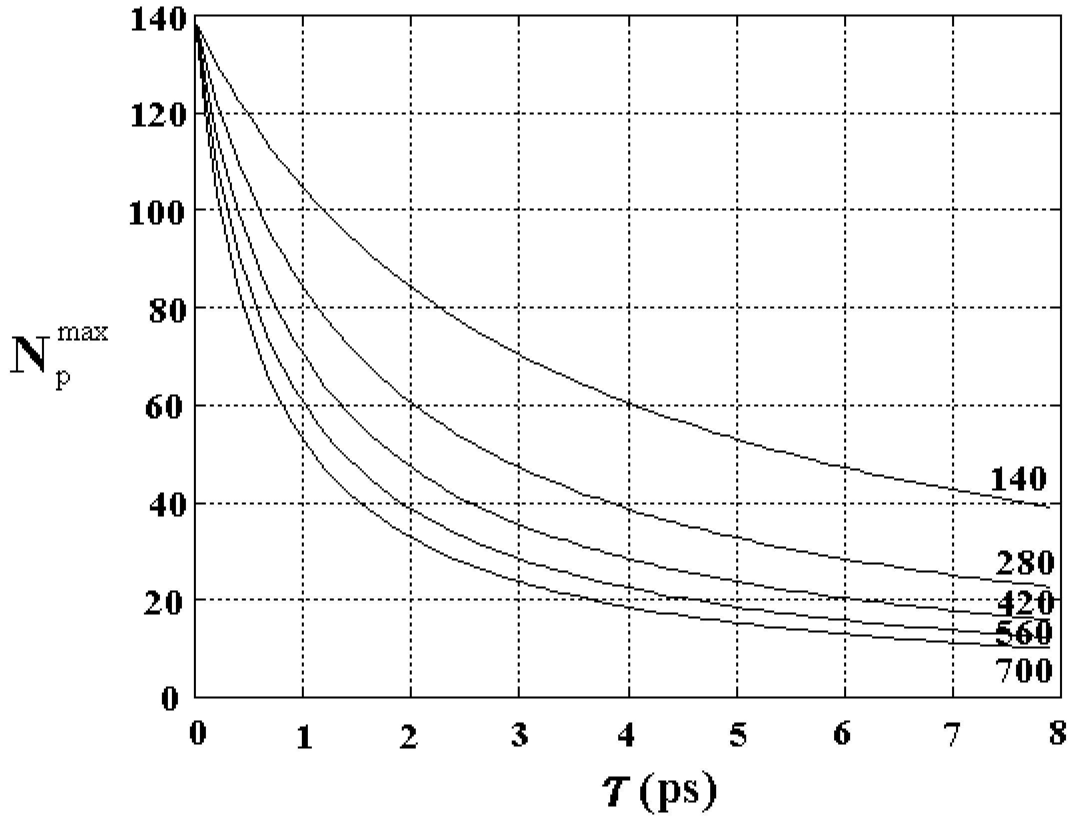

Fig.5 Maximum number of data pulses that compose the sequence to be encrypted versus the temporal length of the pulses τ for different value of the attenuation A of the material, expressed in dB/m.

The number N_P can be properly increased by decreasing the denominator of eq.(21) that is by increasing the reflectivity of the mirrors or by reducing the coefficient of absorption of the material or the temporal length of the 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. 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. The same arguments are valid for the temporal length of the pulses.

These effects can be clearly seen in fig.5 where all the curves related to different values of the attenuation A of the material merge when the pulse length τ tends to zero. If we want to know the maximum theoretical number of bits that can compose the input stream it is necessary to neglect in the denominator of eq.(21) the term related to the pulse length and to suppose the mirrors to have the maximum reflectivity of 99.95%. In this case we obtain that the pulses cannot propagate inside each loop more than 138 times, that is, considering the worst situation N_P =2N, the cryptographic device can theoretically reach the limit of a bit stream of 69 bits. A quite higher number of bits can be reached considering more favourable cryptographic sequences, that is to shuffle the bit so that the first pulses of the input sequence are not the last pulses of the encrypted output sequence.

8. CONCLUSIONS

We presented and designed an all-optical cryptographic device, based on the properties of soliton beams.
The switching properties have been studied, obtaining some useful design criteria that help to design this kind of device.
The operative frequency can be as high as desired and it is limited by the operative frequency of the source that generates the querying pulses and by the response time of the material. It can anyway reach hundreds of GHz.
The maximum number of bits that compose each input sequence have been demonstrated to be equal to 69.

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