All-optical switching and amplification of discrete vector solitons in nonlinear cubic birefringent waveguide arrays

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Abstract

We study all-optical switching based on the dynamical properties of discrete vector solitons in waveguide arrays. We employ the concept of the polarization mode instability and demonstrate simultaneous switching and amplification of a weak signal by a strong pump of the other polarization.

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OCIS codes: 190.0190, 190.4370, 190.5530.
1. Introduction

Discrete spatial solitons are usually introduced as spatially localized nonlinear modes of weakly coupled optical waveguides, and they have recently been observed experimentally in different nonlinear systems. A standard theoretical approach in the study of discrete spatial optical solitons is based on the derivation of an effective discrete nonlinear model and the analysis of its stationary localized solutions—discrete localized modes.

Many studies analyzed both propagation and steering of scalar discrete solitons in nonlinear waveguide arrays, including trapping, reflection, and refraction of an incoming discrete soliton in an array with defects. For waveguide arrays with quadratic nonlinear response, Pertsch et al. suggested an optical switching scheme where a low-power diffractionless beam is coupled parametrically to a pump, resulting in generation of a strong idler beam. Recently, we suggested to control multi-port switching of discrete solitons in waveguide arrays by engineering the coupling between the neighboring waveguides: this induces a change of the dynamic properties of the array through the modification of the effective Peierls-Nabarro (PN) potential, a nonlinear discreteness-induced potential that is responsible for the transverse dynamics of discrete solitons in a waveguide array.

In materials with a nonlinear cubic response, we expect a very rich nonlinear dynamics and coupling between different modes. In particular, coupling between the waves of two orthogonal polarizations can result in the formation of a vector soliton. Vector solitons can be employed for different schemes of all-optical switching schemes, e.g. by employing collisions between orthogonally polarized solitons without or with four-wave mixing (FWM) effects. The FWM effect is responsible for the energy exchange between the two (TE and TM) polarizations. In planar waveguides, the TE mode is known as ‘slow’, while the TM mode— as ‘fast’, because the TE mode has larger propagation constant. Interaction between the
TE and TM modes is known to lead to polarization mode instability\(^9\), so that the TM mode is always unstable with respect to the TE mode. This implies that the fast mode transfers the energy to the slow mode.

The theory of discrete vector solitons developed so far does not include the analysis of the FWM effects (as an example, see Ref. \(^{10}\)). However, the first experimental studies of the vectorial interactions and discrete vector solitons in waveguide arrays\(^{11}\) due to coupling between two orthogonally polarized modes, suggest the importance of the FWM effects demonstrating that the initial phase between the TE and TM modes defines the energy exchange between the modes.

In this Letter, we study numerically the dynamics and switching properties of discrete vector solitons employing the concept of polarization mode instability. We demonstrate an effective switching, control, and amplification of a weak signal by a strong pump of the orthogonal polarization that can be useful for multi-port all-optical switching.

In order to analyze the polarization effects for discrete solitons, we consider a model of birefringent cubic nonlinear waveguide arrays recently fabricated experimentally\(^{11}\), described by the coupled-mode theory within the slowly varying envelope approximation:

\[
\begin{align*}
- i \frac{da_n}{dz} &= V_n^+ \{a_n\} + |a_n|^2 a_n + A |b_n|^2 a_n + B b_n^* a_n^* \\
- i \frac{db_n}{dz} &= V_n^- \{b_n\} + |b_n|^2 b_n + A |a_n|^2 b_n + B a_n^2 b_n^*,
\end{align*}
\]

where \(V_n^\pm \{a_n\} = \pm a_n + V (a_{n+1} + a_{n-1})\), \(a_n\) and \(b_n\) are the normalized envelopes of the TE- and TM-polarized components of the electric field, respectively, \(z\) stands for the propagation distance, \(V\) is the coupling parameter assumed to be the same for both polarizations (both modes have the similar transverse extensions). Nonlinear coefficients \(A\) and \(B\) characterize the cross-phase-modulation and the FWM effects (weighted with the self-focusing term),
respectively. In our study, we use the experimental parameters of this model as defined in Ref. 11, i.e. $A = 1$, $B = 0.5$, and $V = 0.92$. The normalized power,

$$P = P_a + P_b = \sum_n (|a_n|^2 + |b_n|^2),$$  \hspace{1cm} (2)

and Hamiltonian, $H = -\sum_n (H^a_n + H^b_n + H^{ab}_n)$, where

$$H^{a,b}_n = \pm|a_n|^2 + V(a_n^* a_{n+1} + a_{n+1}^* a_n) + \frac{1}{2}|a_n|^4,$$

$$H^{ab}_n = |a_n|^2|b_n|^2 + \frac{B}{2} (b_n^2 a_n^2 + a_n^2 b_n^2)$$  \hspace{1cm} (3)

are conserved in the dynamics, and they both play an important role for checking numerical accuracy and for estimation of the realistic power of the switching-amplification process (e.g., $P_{\text{real}} \approx 56 \times P [W]$ in the AlGaAs waveguide array used in Ref. 11).

An important step of our analysis is a choice of the appropriate initial profiles for both modes. Since the exact solution to Eq. (1) is not known, we select a truncated sech-like profile:

$$a_n(0) = a_0 \text{sech}[a_0(n - n_{ca})/\sqrt{2}] \ e^{-ika(n-n_{ca})} \ e^{i\phi_a},$$

$$b_n(0) = b_0 \text{sech}[b_0(n - n_{cb})/\sqrt{2}] \ e^{-ikb(n-n_{cb})} \ e^{i\phi_b},$$  \hspace{1cm} (4)

for $n - n_{ca} = n - n_{cb} = 0$, $\pm 1$, and $a_n(0) = b_n(0) = 0$, otherwise. Parameters $a_0$ and $b_0$ are the initial amplitudes, $k_a$ and $k_b$ are the initial kicks (transverse angles), $n_{ca}$ and $n_{cb}$ are the initial center positions, and $\phi_a$ and $\phi_b$ are the input phases, for both TE and TM modes, respectively. As has been verified earlier, this ansatz provides a very good agreement in the scalar case, when just one mode propagates in the array. A specific choice of the initial input is not a restriction to our analysis, because a discrete soliton is a self-adjusting mode, and an energy excess is emitted in the form of radiation modes. We have carried out numerical simulations with other profiles, and the dynamic behavior was found to be similar.
In the polarization-induced dynamics, a fast mode is unstable with respect to its transformation into a slow mode. Numerically, we observe that we can invert this polarization instability with an appropriate use of the initial phase shift. When the initial phase shift is 0 or $\pi$ (linearly polarized), the TM mode always transfers a part of its energy to the TE mode. On the other hand, if the initial phase shift is $\pi/2$ (elliptically polarized), we observe a reversed effect. Thus, we can control the energy transfer by choosing the initial phase shift between both modes at the input. In some cases, e.g. when we consider large propagation distances, the energy exchange can be complete. In this paper, we study the linearly polarized case only, because the maximum power gain for the TE mode, 
\[
\frac{P_a(z_{\text{max}}) - P_a(0)}{P_a(0)},
\]
observed in this situation ($\sim 6000\%$) is higher than for the elliptically polarized case ($\sim 100\%$). This asymmetry in the polarization instability is a very interesting feature, but here we are interested only in an efficient all-optical switching scheme based on this effect.

In our numerical simulations, we take $z_{\text{max}} = 50$ and an array of 110 waveguides. We made sweeps of the system parameters and observe the TE gain. On a phase diagram in Fig. 1, we show the TE (signal) power gain vs. the TM (pump) mode input angle $k_b$ – the TM (pump) power content $P_b(0)$ space, for a small TE initial power $P_a(0) = 0.03$ and zero angle $k_a = 0$, and for initial linear polarization. The whiter region marks a high gain limit (up to 60 times), while the black region marks a low gain (0.7). As expected, the maximum gain is achieved when the angle of the pump is near zero, and when the amplitude to the pump is the highest. In Fig. 2 (point “A” in Fig. 1), we show the longest switching case (13 sites) which is associated with a low power gain, $\sim 70\%$. In Fig. 3 (point “B” in Fig. 1), we show a switching for 4 sites with a medium range power gain of $\sim 800\%$. In Fig. 4 (point “C” in Fig. 1), we show an example of strongly suppressed switching with a huge power
gain of $\sim 6.000\%$. It is very important to note that the TE signal has a very low power, approximately 1.7 W. Another important remark is that the TE signal has no initial kick. With that, we want to be emphatic about the real possibilities of the implementation of our concept. The idea suggested in Fig. 1 is that a very small unkicked signal arriving at the middle of the array can, as a consequence of the polarization mode instability, be amplified in any amount from 70% to 6000%, by judiciously choosing the pump (TM) input angle and the pump power.

This effect is possible due to an interplay between two effects, the polarization instability and the array discreteness. The lower the input power, the lower is the PN barrier, and the larger is the distance from the input waveguide that the soliton can propagate. Before the soliton gets trapped, it loses part of its energy in the form of radiation modes, adjusting its profile to the discrete soliton mode corresponding to the output waveguide. Thus, for a low power level (Fig. 2), discrete solitons will have more transversal mobility and will be trapped in a waveguide located far from the input region. At high enough power level, the switching will be at a near (Fig. 3) or null (Fig. 4) distance from the input waveguide.

In conclusion, we have suggested a novel multi-port amplifying/switching scheme, which uses the typical polarization instability property of vector solitons as well as the PN concept due to the system discreteness.

The authors acknowledge a support from a Comisión Nacional de Investigación Científica y Tecnológica and Fondo Nacional de Desarrollo Científico y Tecnológico. R.A. Vicencio’s e-mail address is rodrigov@fisica.ciencias.uchile.cl

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Fig. 1. TE gain vs. initial kick $k_b$ and the normalized power $P_b(0)$ of the TM mode ($k_a = 0, P_a(0) = 0.03$).

Fig. 2. Switching by 13 sites ($k_b = -1, P_b(0) = 3.39$). The gain is about 70% (point “A” in Fig. 1).

Fig. 3. Switching by 4 sites ($k_b = -0.8, P_b(0) = 3.63$). The gain is about 800% (point “B” in Fig. 1).

Fig. 4. Trapping without switching ($k_b = 0, P_b(0) = 3.97$). The gain is about 6.000% (point “C” in Fig. 1).
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