Optical switching with nonlinear optical loop mirror using vector soliton states in a nearly isotropic fiber

Hee Yeal Rhy, Byoung Yoon Kim, Hai-Woong Lee

Department of Physics, Korea Advanced Institute of Science and Technology, Taejon 305-701, South Korea

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Abstract

Optical switching using a nonlinear optical loop mirror, which exploits unequal nonlinear phase shifts acquired by linearly and circularly polarized solitons that counterpropagate the loop, is investigated. The device totally reflects small amplitude light waves and transmits maximally switched soliton-like pulses nearly completely. The device works for a fiber loop of birefringence of less than $10^{-8}$ and pulses of width of the order of a few hundred femtoseconds. © 1998 Elsevier Science B.V.

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1. Introduction

Since the first proposal [1], the nonlinear-optical loop mirror (NOLM) has received great attention as a fast optical switch in future optical communication systems [2]. Self switching with the NOLM is accomplished by breaking the loop symmetry for counterpropagating pulses and thereby causing them to acquire unequal nonlinear phase accumulations. The standard NOLM employs an asymmetric coupler to break the symmetry. One disadvantage of a switch using an asymmetric coupler is that small amplitude input pulses do not produce zero output. Various alternative schemes of breaking the symmetry with the use of a symmetric (50:50) coupler have been proposed and demonstrated. They include insertion of an asymmetrically located amplifier within the loop [3], alternation of the principal propagation axes along a birefringent fiber [4], and use of a dispersion decreasing fiber [5]. The first scheme using an asymmetrically located amplifier has an added advantage in that the switching threshold is lowered and the switching length is reduced. The latter two schemes are attractive as switching can be achieved with a symmetric coupler and yet without any gain element. There are, however, problems such as the necessity of having to match the lengths of two birefringent fiber sections to within sub-millimeters and manufacturing a dispersion decreasing fiber of desired dispersion profiles.

In this paper we propose another scheme which is based on unequal nonlinear phase accumulations experienced by linearly and circularly polarized solitons. The method, designed to work with a symmetric coupler, requires a loop made of a nearly isotropic fiber. The device based on this method totally reflects a small amplitude wave and transmits maximum switched soliton-like pulses of a few hundred femtoseconds nearly completely.

2. Pulse propagation in an isotropic fiber

The evolution of a light pulse in a weakly birefringent nonlinear dispersive fiber is described by the coupled nonlinear Schrödinger equations [6,7],

\[
\frac{i}{i} \frac{\partial U}{\partial t} + \beta U + \frac{1}{2} \frac{\partial^2 U}{\partial t^2} + \left( |U|^2 + \frac{2}{3} |V|^2 \right) U + \frac{1}{3} V^2 U^* = 0, \tag{1}
\]

\[
\frac{i}{i} \frac{\partial V}{\partial t} - \beta V + \frac{1}{2} \frac{\partial^2 V}{\partial t^2} + \left( |V|^2 + \frac{2}{3} |U|^2 \right) V + \frac{1}{3} U^2 V^* = 0, \tag{2}
\]
where $U$ and $V$ are the slowly varying envelopes of the two linearly polarized components of the electric field of the pulse, $z$ and $t$ are, respectively, the normalized distance along the fiber and normalized time, and $\beta$ is half the difference between the propagation constants and is given by

$$
\beta = 0.644 \pi^2 c (\Delta \tau)^2 \Delta n / (\lambda |D|),
$$

(3)

where $\lambda$ and $c$ are, respectively, the wavelength and velocity of light in vacuum, $\Delta \tau$ the temporal width (FWHM) of the pulse, $\Delta n$ the difference between refractive indices along the fast and slow axes, and $D$ denotes the group velocity dispersion. The last term on the left hand side of Eqs. (1) and (2) is negligible if the fiber is strongly birefringent, but cannot be neglected in our case of a nearly isotropic fiber.

We assume that the loop birefringence is sufficiently small so that the solutions of the coupled equations (1) and (2) are described approximately by those for an isotropic fiber. When $\beta = 0$, the coupled equations (1) and (2) are known to have various stationary vector soliton solutions [8] such as linearly polarized soliton states given by

$$
U = \sqrt{2} \alpha \text{sech} \left( \sqrt{2} \alpha t \right) \exp(i \alpha z), \quad V = 0,
$$

(4)

$$
U = 0, \quad V = \sqrt{2} \alpha \text{sech} \left( \sqrt{2} \alpha t \right) \exp(i \alpha z),
$$

(5)

and circularly polarized states given by

$$
U - iV = \sqrt{6} \alpha \text{sech} \left( \sqrt{2} \alpha t \right) \exp(i \alpha z), \quad U + iV = 0,
$$

(6)

$$
U + iV = \sqrt{6} \alpha \text{sech} \left( \sqrt{2} \alpha t \right) \exp(i \alpha z), \quad U - iV = 0,
$$

(7)

where $\alpha$ is the soliton parameter inversely proportional to the soliton period. It should be noted that the total pulse energy

$$
E = \int_{-\infty}^{\infty} (|U|^2 + |V|^2) \, dt
$$

is $2\sqrt{2} \alpha$ for a linearly polarized soliton of Eq. (4) or (5), but is $3\sqrt{2} \alpha$ for a circularly polarized soliton of Eq. (6) or (7). Consequently, the linearly polarized soliton acquires more phase shift than the circularly polarized soliton for the same pulse energy. This difference plays a key role in our scheme to be described below.

3. Analysis of switching

Let us consider the arrangement shown in Fig. 1 with a 50:50 coupler and a polarization controller installed asymmetrically in the loop. We wish to design the device such that the loop works as a total reflector in the linear regime and as a total transmitter in the soliton regime.

![Fig. 1. Schematic diagram of the proposed nonlinear optical loop switch.](image)

In the linear regime, the transmitted and reflected waves are given respectively by

$$
E_t = \frac{i}{2} (I A - A^T I) E_i,
$$

(9)

$$
E_r = \frac{i}{2} (I A + A^T I) E_i,
$$

(10)

where $E_i$, $E_t$, and $E_r$ are the amplitudes of the transmitted, reflected and incident waves, respectively, $A$ represents the action of the polarization controller, and $I$ is the coordinate inversion matrix given as

$$
I = \begin{pmatrix}
1 & 0 \\
0 & -1
\end{pmatrix}.
$$

(11)

It can easily be seen that, for a linearly polarized input wave, the condition $E_i = 0$ is satisfied if $A$ is given by

$$
A = \frac{1}{\sqrt{2}} \begin{pmatrix}
-i & -1 \\
1 & i
\end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix}
0 & -1 \\
1 & 0
\end{pmatrix} \begin{pmatrix}
1 & i \\
i & 1
\end{pmatrix}.
$$

(12)

The action represented by Eq. (11) corresponds to a 45° tilted quarter wave plate followed by a 90° rotation in bulk optics and can be realized by setting the polarization controller appropriately.

With the polarization controller set according to Eq. (11), we now consider the operation of our device to be in the soliton regime. We assume that the pulse entering the directional coupler is a linearly polarized soliton of the form $\sqrt{E} \text{sech} t$ ($2\sqrt{E}$ represents the normalized energy of the incident soliton pulse). The incident wave is split into two, one in a linearly polarized state represented by

$$
U = \sqrt{E/2} \text{sech} t, \quad V = 0,
$$

(13)

and the other, after the action of the polarization controller, in a circularly polarized state represented by

$$
U - iV = \sqrt{E} \text{sech} t, \quad U + iV = 0,
$$

(14)

The two waves experience different amounts of nonlinear phase shift upon traversal of the loop. The phase shift acquired by the linearly polarized soliton of Eq. (12) is given, according to the soliton phase model [9,10], by

$$
\phi_{l,p} = 2 \left( \sqrt{E/2} - 1/2 \right)^2 z
$$

where $\sqrt{E/2} > 1/2$ is assumed. Similarly, one can calcu-
late the phase shift acquired by the circularly polarized soliton of Eq. (13) and obtain
\[
\phi_{CP} = \frac{4}{3} \left( \sqrt{E/2} - \sqrt{3}/4 \right)^2 \zeta.
\]  

(15)

where \( \sqrt{E/2} > \sqrt{3}/4 \) is assumed. Thus the nonlinear phase shift difference between two counterpropagating waves is
\[
\delta \phi = \phi_{LP} - \phi_{CP} = \left[ E - \left( 3\sqrt{2} - 2\sqrt{3} \right) \sqrt{E} \right] z/3
\]

(16)

and the first nonlinear phase shift of \( \pi \) occurs at
\[
z_0 = 3\pi/\left[ E - \left( 3\sqrt{2} - 2\sqrt{3} \right) \sqrt{E} \right].
\]

(17)

With the loop length given by Eq. (17), the incident soliton is totally transmitted.

4. Results and discussion

Fig. 2 shows the transmitted pulse energy versus input pulse energy, obtained through analytic calculation based on Eq. (16) as well as through numerical computation of Eqs. (1) and (2) with \( \beta = 0 \). The loop length was adjusted to 5.6 corresponding to the value of \( z_0 \) at \( E = 3 \) at which the circularly polarized pulse propagating the loop clockwise satisfies the fundamental soliton condition. Analytic calculation and numerical simulation agree well with each other for input energy \( \leq 6 \). The discrepancy between the two calculations at higher energies is due to high-order soliton effects. This, however, is not much of our concern

because the detailed structure in the high energy region is known to be washed out by the soliton self-frequency shift effect [11]

Fig. 3 shows the intensity profiles of the input and output pulses. At an energy of 0.5, 99% of the pulse is reflected. On the other hand, at an energy of 3.0, 99% of the pulse is transmitted. The width of the transmitted pulse is seen to be narrower than that of the input pulse, in agreement with the previous analysis [2].

Our analysis up to this point has been carried out for an isotropic fiber. In reality, however, some degree of birefringence is unavoidable whether it is intrinsic or induced from bending. In some cases, birefringence is induced intentionally to suppress the effect arising from random rotations in polarization. For our scheme to work, however, the fiber is required to have low birefringence, because, in the presence of birefringence, the circularly polarized pulse is no longer a stationary state and becomes even unstable at large birefringence [7,12]. In other words, our scheme requires sufficiently low birefringence so that the circularly polarized pulse as well as the linearly polarized pulse maintain their polarization states as they propagate the loop. From computer simulations of Eqs. (1) and (2) for various \( \beta \) values, we determine that this require-
ment is satisfied if $\beta \leq 0.1$. If we take a 100-fs pulse and a fiber with dispersion $-10 \text{ ps/km/nm}$ at the wavelength of 1.55 $\mu$m, this inequality translates into $\Delta n \leq 2 \times 10^{-7}$. Typical low birefringent fibers have birefringence less than $10^{-8}$, and thus our scheme is expected to work as long as the pulse width is of the order of a few hundred femtoseconds or less.

The above problem of the circularly polarized state not being a stationary solution can partly be eliminated by using an elliptically polarized pulse instead of a circularly polarized pulse. It has been shown that in a birefringent fiber there exist, in addition to the fast and slow linearly polarized stationary solitons, stationary elliptically polarized solitons which can propagate without change of the state of polarization [13]. One can thus adjust the polarization controller to convert the linearly polarized pulse to the stationary elliptically polarized pulse and let it interfere with the counterpropagating linearly polarized pulse. In this case the linearly polarized pulse that interferes with the elliptically polarized pulse must be on the slow axis because of the instability of the fast mode [12]. Even with this novel idea, the loop birefringence needs still to be kept small, because the two pulses, elliptically and linearly polarized, should be recombined at the same time.

In conclusion we have proposed a new operational method of the NOLM which takes advantage of the fact that linearly and circularly polarized solitons in an isotropic fiber acquire different amounts of phase shift. Because our scheme uses a symmetric coupler, the device is totally reflective for small input pulses. The maximum transmission in the soliton regime is estimated to reach $\sim 99\%$.

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References