

All-Optical Signal Routing Using Interaction of Mutually Incoherent Spatial Solitons

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(Received July 2, 2001)

We propose an all-optical switch or router that is based on the interaction of counterpropagating mutually incoherent spatial optical solitons. The concept is demonstrated experimentally by nonlinear collision of spatial solitons in a photorefractive planar waveguide in strontium barium niobate.

Keywords: Optical switching; spatial solitons

OCIS codes: 230.7370, 060.1810, 160.5320

Since the first experimental demonstration of photorefractive spatial solitons in 1993 [1, 2] self-focusing and defocusing of light beams in photorefractive materials are the subject of increasing interest, because these effects enable diffraction-free or soliton-like propagation of optical light waves [3–7]. A bright spatial soliton is a collimated light beam that propagates through the nonlinear material without changing its transverse profile. Diffraction is compensated by the self-focusing effect, i.e., by the light-induced positive refractive index changes in the plane perpendicular to the propagation direction of the optical beam.

Among the most interesting properties of optical solitons is the nonlinear interaction that takes place when two solitons intersect or propagate close enough within the crystal. In Kerr media it is well known [8] that solitons in most respects behave as particle-like objects, and the identity of each soliton is maintained in the interaction. However, solitons in photorefractive crystals behave completely different because of the saturable nonlinearity [9]. Here repulsive and attractive forces between the interacting solitons can lead to fusion, fission, spiraling, or energy exchange [10–12]. Compared to typical

Kerr media that require high power laser beams to form spatial solitons, it has been experimentally confirmed that photorefractive spatial solitons can exist at optical powers of a few μW [6, 7]. Furthermore, very recently photorefractive soliton formation has been demonstrated for infrared light at the telecommunication wavelengths of 1.3 and 1.5 μm [13]. In conjunction with the low power level the interacting forces between solitons promise potential applications as photonic elements, e.g., all-optical switches, directional couplers, or beam deflectors.

The interaction of coherent photorefractive solitons critically depends on the relative phase of the interacting light beams [11, 12]. However, in a soliton-based device it may be difficult to keep this phase relation constant during propagation of the involved beams, and the output of the interaction will be rather difficult to control. To avoid these potential problems, one may consider the interaction of mutually incoherent solitons, where phase relations do not affect the interaction [14, 15]. In this contribution we will show that such an interaction scheme can be used to build an all-optical switch and router that is based on attractive or repulsive forces between nearly counterpropagating light beams. The feasibility of such a device is demonstrated experimentally by nonlinear collision of spatial solitons in a photorefractive planar waveguide in strontium barium niobate (SBN61).

Our concept is based on interaction of mutually incoherent solitons. These solitons do not interfere with each other, and the light intensity always increases in the overlap region. When two of these solitons propagate parallel but close to each other (at a distance comparable to the soliton width), or intersect under a small angle (smaller than the critical angle for guiding in the induced waveguide), their beam trajectories move closer to each other due to the interaction or eventually fuse together, indicating an attractive force between the beams [14]. However, in a recent paper it has been shown that the interaction can also lead to repulsive forces [15]. This effect takes place when the separation of the involved parallel propagating solitons is of the order of some soliton widths. In this situation, the resulting refractive index distribution along the direction of the externally applied electric field shows a negative dip in the overlap region that resembles the self-defocusing condition. Therefore the two beams can repel each other.

In Fig. 1 two possible schemes of an all-optical switch and router are displayed. In Fig. 1(A) two mutually incoherent spatial solitons (signal and control beam) counterpropagate in a biased photorefractive crystal. The initial beam separation is of the order of some soliton widths, thus resulting in a repulsive force. When the control beam is switched on, the signal beam is directed to a certain desired position (output 2) and can, in principle, be

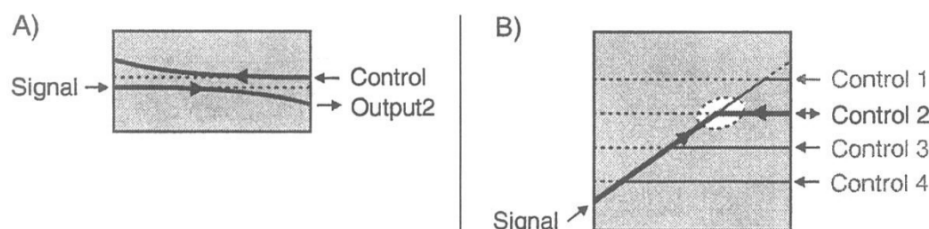


Figure 1. Scheme of an all-optical switch and router. (A) Repulsive interaction of two counterpropagating mutually incoherent solitons (signal and control). (B) All-optical router based on attractive forces of intersecting solitons. The signal beam can be directed to different output channels.

coupled into an optical fiber. Another concept allows for the routing of one signal beam into different output channels. In the scheme shown in Fig. 1(B), the trajectory of the signal beam intersects the trajectories of different control beams under a small angle that allows for trapping of the signal light intensity in the self-induced waveguide of one of the control beams. For example, optical routing of the signal beam to the output channel 2 is achieved by switching on the (counterpropagating) control beam 2 while the other control beams are switched off.

For mutually incoherent solitons, there is no principal difference of the interaction for co- or counterpropagating beams, respectively. However, there are some advantages for the counterpropagating case in optical switching regarding the proposed concept in Fig. 1. First, a spatial separation of signal and control beam can be done by a simple beam splitter, and second, in the scheme of Fig. 1(B) the spatial position of each output channel is fixed by the corresponding control beam. For an analogous copropagating scheme, problems in a proper spatial fixing of the output channel might occur because of the self-bending of the soliton trajectories [7, 16].

To demonstrate the principle suitability of the concept, experiments are performed in a planar waveguide in Rh-doped SBN61. Waveguide fabrication is done by ion implantation which results in an about $4.5 \mu\text{m}$ -thick waveguiding layer [17]. The light propagation length inside the waveguide is 7.8 mm. Using silver paint electrodes an electric field can be applied along the ferroelectric c -axis that is directed perpendicular to both the waveguide normal and the propagation direction.

The experimental setup is depicted in Fig. 2. The extraordinarily polarized light of two different helium neon lasers ($\lambda = 632.8 \text{ nm}$) is coupled from different sides (denoted by -1- and -2-, respectively) through the polished endfaces into the waveguide using a combination of cylindrical and

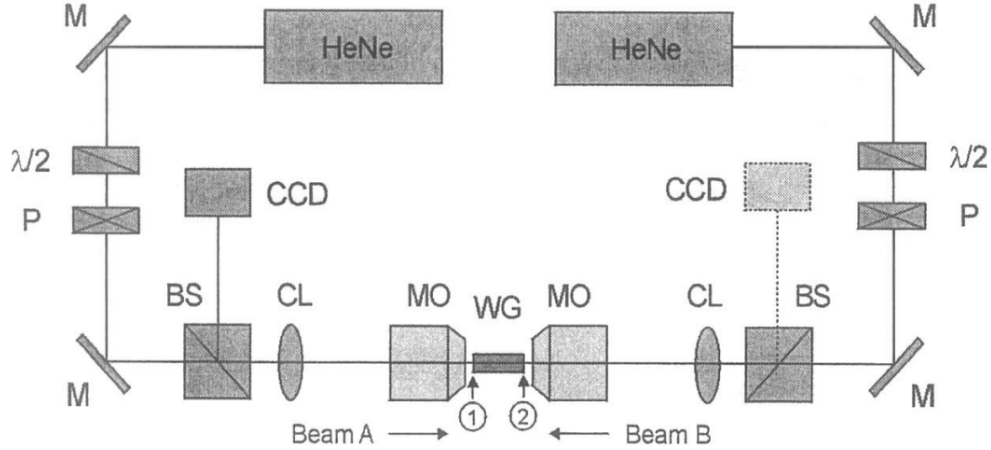


Figure 2. Experimental setup. HeNe's, helium neon lasers; M's, mirrors; $\lambda/2$, half wave plates; P's, polarizers; BS's, beam splitters; CL's, cylindrical lenses; MO's, microscope lenses; WG, waveguide; CCD, CCD camera. The beams entering from the left and from the right are labeled by A and B, while the waveguide's endfaces are numbered by -1- and -2-.

microscope lenses. The CCD camera images one of the endfaces. The intensity profiles of both beams can be monitored in this way: the incoupled beam is detected by its intensity reflected at the polished endface, while the second outcoupled beam is detected directly.

The intensity ratio $r = I_s/I_d$ of the solitons can be adjusted by changing the input power $P_s = I_s \times A$ of the beams, where I_s is the soliton intensity, $A = d \times 4.5 \mu\text{m}$ is the effective area, and d is the soliton (FWHM) width. The dark irradiance I_d is dominated by the high dark conductivity of the implanted waveguide layer and has a fixed value of $I_d = 40 \text{ W/cm}^2$ for all measurements [13]. No further background light is used.

At first we investigate the beam deflection of counterpropagating solitons. Two beams A and B are launched anti-parallel into the waveguide with an initial distance of some tens of micrometers. Beam A enters through endface -1-, while B enters through endface -2-. The incoupled power of the two beams are $P_A = 2 \times 10^{-1} \text{ mW}$ and $P_B = 5 \times 10^{-2} \text{ mW}$. The FWHM width of the two beams on the two endfaces are $16 \mu\text{m}$ and $14 \mu\text{m}$, which gives an intensity ratio of $r_A \approx 7$ and $r_B \approx 2$, respectively. When launched separately and an electric field of $E = 5.6 \text{ kV/cm}$ is applied, both beams form spatial solitons. Self-bending of the two soliton trajectories causes the solitons to move laterally on the respective endface [7, 16]. This is caused by the non-local diffusion mechanism of charge transport that deflects the light towards the negative c -axis of the SBN sample. For both beams we measure a movement of about $60 \mu\text{m}$.

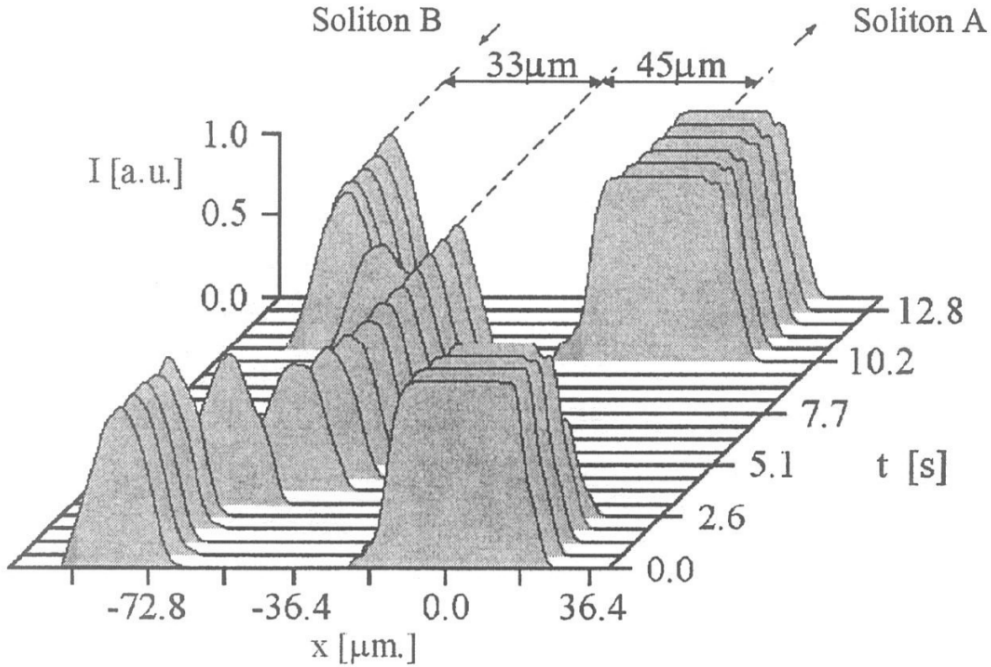


Figure 3. Demonstration of the optical switch. Shown are the spatial positions of the two interacting beams on endface -1-. The initial distance without interaction is $45 \mu\text{m}$. When both beams interact, the solitons are repelled and are finally separated by $78 \mu\text{m}$. The corresponding time constants for switching of soliton B are $\tau_{\text{on}} = 0.6 \text{ s}$ (soliton A on) and $\tau_{\text{off}} = 1.1 \text{ s}$ (soliton A off).

When the two beams are switched on together, we observe both, attractive and repulsive forces, depending on the size of the initial distance of the solitons. In general, larger deflection is achieved for repulsive forces. This may be of importance for the design of an optical switch, because it decreases cross talk between the two possible output channels. An example is given in Fig. 3 where the positions of the two beams are shown on endface -1- where beam A enters the sample. The initial distance without interaction was $45 \mu\text{m}$ on each endface which is about three times the soliton width. When both beams are present and interact, the solitons are separated by $78 \mu\text{m}$, giving a deflection of soliton B of $33 \mu\text{m}$. The corresponding time constants can be determined to be $\tau_{\text{on}} = 0.6 \text{ s}$ (A is switched on, B is deflected) and $\tau_{\text{off}} = 1.1 \text{ s}$ (A is switched off, B moves back to its initial position). Here time constants are defined as the time where the solitons have been shifted half of the final deflection distance.

In a second experiment, we investigate the interaction of two solitons that intersect under a small angle inside the sample. This is the basic interaction mechanism for the all-optical router shown in Fig. 1(B). Starting from the

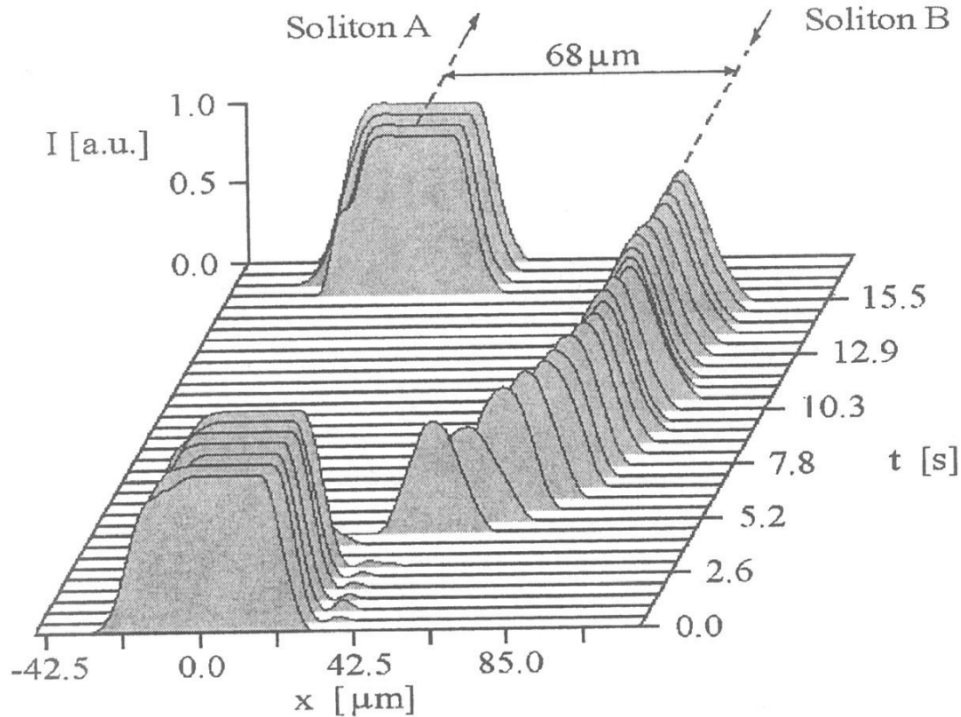


Figure 4. Example of counterpropagating soliton interaction. The intersection angle is $\theta = 12.2$ mrad and the distance on endface -1- is $68 \mu\text{m}$. At $t = 3$ s soliton A is switched off, and soliton B is released and moves back to its original position. At $t = 15$ s soliton A is switched on and traps soliton B again.

exactly counterpropagating case, we slightly change the direction of beam A, thus changing the angle between beams A and B from 180° to $(180^\circ + \theta)$, while keeping the initial distance of both beams on the endface -1- constant. In Fig. 4 we show an example for input powers of $P_A = 5.8 \times 10^{-2}$ mW and $P_B = 7.5 \times 10^{-2}$ mW. The soliton width is about $14 \mu\text{m}$ and $12 \mu\text{m}$ for $E = 5.6$ kV/cm, and the distance on endface -1- is $68 \mu\text{m}$. The interaction is shown for an intersection angle of $\theta = 12.2$ mrad which is below the critical angle for guiding in the soliton-induced waveguide channel [14]. When soliton A is on, the trajectories of the solitons are merged together, and both beams propagate in the same jointly formed waveguide channel. The intensity ratios of both beams independently ($r_A \approx 2.3$ and $r_B \approx 3.5$), as well as in case when they are merged together ($r_{AB} \approx 6$), are close to the minimum of the corresponding existence curve [6]. Therefore the width of the solitons does not change significantly during interaction. At $t = 3$ s soliton A is switched off, and soliton B is released and moves back to its original position. At $t = 15$ s soliton A is switched on and traps soliton B again. Note that the time

constants for trapping and releasing of soliton B are quite different. This can be explained as follows. On the one hand, the responsible mechanism for trapping is a refractive index change in the small intersection region only, and it has a time constant well below 500 ms (sampling rate of the CCD is about 2 Hz here). This time constant is comparable to the soliton's build up time to the steady-state. On the other hand, when soliton A is switched off, soliton B is still trapped in the waveguide channel of soliton A . Because this channel is not stable anymore, the trajectory of soliton B moves in a continuous way towards its former position, erasing the former waveguide channel while writing a new, spatially shifted one, which leads to a larger time constant for releasing that is about 2 s in this example.

A simple estimation shows that several parallel control/output channels can be formed in our waveguide sample. The device does not suffer from interaction of the different control beams, because during operation only one of the channels is active, i.e., this channel guides the control light and redirects the signal to the desired output channel. Furthermore, by using higher intensities for the control beams, the switching time constant can be considerably decreased. At the same time, the critical angle for guiding in the soliton-induced channel will be increased, thus allowing for a higher density of parallel control/output channels of the device.

In summary, we have demonstrated the concept of an all-optical switch and router that is based on the interaction of counterpropagating mutually incoherent spatial solitons. Experimental results for the nonlinear collision of solitons in a planar waveguide in SBN61 have shown the principle feasibility of the device. Even if the switching speed is in the range of 1 s and therefore too low for a real application, this work shows the potential use of soliton-based devices for use in telecommunication and signal processing.

ACKNOWLEDGEMENT

Financial support of the Volkswagen Foundation (grant ZN1154) is gratefully acknowledged.

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