Asymmetric optical Y junctions and switching of weak beams by using bright spatial-soliton collisions

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We show that a collision between two bright spatial solitons acts as an asymmetric optical Y junction and, in specific cases, as an optical switch for the weak beams that they guide. The output energy of the probe beams in each optical channel can be controlled by adjustment of either the relative direction or the phase of the two colliding solitons or by a change in the wavelength of the probe beams. A physical description of such behavior based on the diffraction of the incident probe beams by a diffraction grating formed by the spatial-soliton collision profile is presented.

An intense optical beam can guide a second, weak beam when it propagates in an intensity-dependent refractive-index medium. The self-guided beam phenomenon was first established theoretically,[1] but of remarkable practical applications were the subsequent experimental demonstrations of the guidance of probe (weak) beams by bright[2] and dark[3] spatial solitons in Kerr-type nonlinear media. The use of spatial solitons as optical channels for probe beams has a direct effect on the development of logical and interconnecting devices. In fact, the latest experiment also showed the formation of a symmetrical optical Y junction. There the transient evolution of an initial intense profile into two dark spatial solitons in a self-defocusing medium ($n_2 < 0$) was used to split the energy of the probe beam equally into the two formed optical channels. In a self-focusing medium ($n_2 > 0$) a similar use of high-order soliton formation is not so evident, because the solitons do not separate in the absence of nonsymmetric perturbations.[4] A recent proposal for an optical switch is based on the interaction (attraction, repulsion, or merging) of two neighboring bright spatial solitons, according to their phase difference.[5,6] However, further applications of soliton waveguides will require a more comprehensive understanding not only of the soliton dynamics itself but also of the specific behavior followed by the probe beams that they guide. For example, it was noted[7] that light guided by dark spatial solitons exhibits an almost linear behavior when the solitons cross, in spite of the intrinsic nonlinear characteristics of a soliton collision.

In this Letter we study the evolution of the probe beams when two bright spatial solitons, acting as optical channels, collide. We find that the input probe-beam energies can be split into the two emerging soliton channels in a controlled way, by proper adjustment of the angle at which the two solitons cross, the relative phase of the colliding solitons, or the wavelength of the probe beams. Such an asymmetrical junction has the additional advantage that, by adjusting the parameters of the interacting solitons, it is possible for one to control actively the switching of the probe beam into just one soliton-based optical channel, without modifying the soliton junction itself.[6]

In the standard two-dimensional approach, the simultaneous propagation of an intense (pump) beam and a probe beam is described by[2]

$$i\frac{\partial A_1}{\partial Z} = -\frac{1}{2}\frac{\partial^2 A_1}{\partial X^2} - |A_1|^2 A_1\,, \tag{1}$$

$$i\frac{\partial A_2}{\partial Z} = -\frac{1}{2} r_n r_k \frac{\partial^2 A_2}{\partial X^2} - \beta |A_1|^2 A_2\,, \tag{2}$$

where the subscript $i = 1$ corresponds to the pump-beam parameters. In Eqs. (1) and (2), A_i are the transversal beam envelopes normalized to $\sqrt{P_0}$, with $P_0 = n_{01}/n_2 L_d$ being the transversal peak power associated with the first-order soliton solution of Eq. (1), n_2 is the Kerr coefficient of the medium, and $L_d = n_{01}{}^2 k_{01}{}^2 x_0{}^2$ is the dimensionless diffraction constant. Moreover x_0 is the initial transversal width of the intense beam, $X = x/x_0$ and $Z = n_{01}k_{01}z/L_d$ are the normalized transversal and propagation distances, respectively, $\beta = 2/r_k$, and $r_n = n_{01}/n_{02}$ and $r_k = k_{01}/k_{02}$ are the ratios of the linear refractive indices and wave numbers, respectively.

To investigate the behavior of the guided probe beam A_2 during a bright soliton optical channel crossing, we use

$$A_1(X,0) = \text{sech}(X + c)\exp[-iv(X + c) + i\phi] + \text{sech}(X - c)\exp[iv(X - c)] \tag{3}$$

as the initial condition for A_1. Equation (3) represents two identical spatial-soliton beams, initially separated by $2c$ and propagating at angles $\pm\theta$ with respect to the Z axis, where $\tan\theta = v$. On the other hand, we use $A_2(X,0) = \text{sech}(X - c)\exp[-iv(X - c)]$ as the initial condition for the probe beam, which is close to the single-mode solution for an optical waveguide with a hyperbolic-secant transversal refractive-index distribution.[8]

A typical numerical solution of Eqs. (1) and (2) is depicted in Fig. 1 for an in-phase ($\phi = 0$) soliton collision. Figure 1(a) shows the bright spatial-soliton collision. As expected, the two solitons

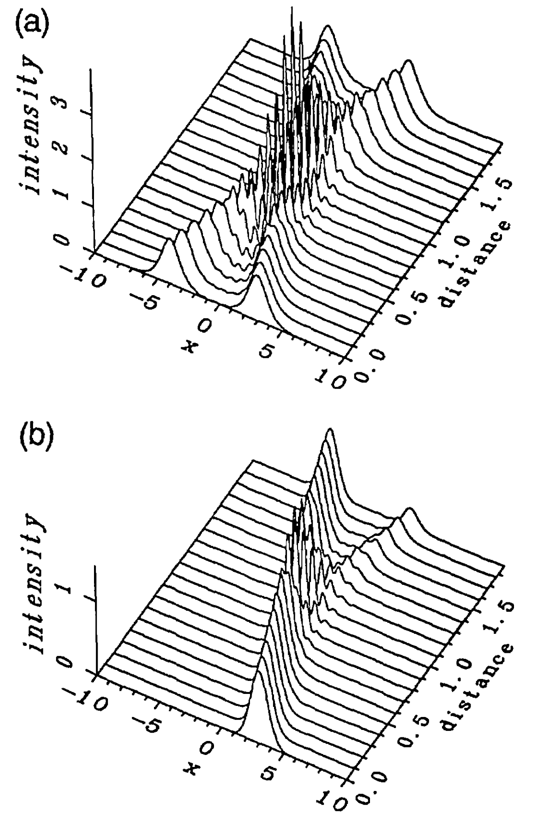

Fig. 1. Optical Y junction formed by the collision of two bright spatial solitons: (a) the soliton collision, (b) the behavior followed by the probe beam. The parameters are $v = 1.2$, $r_n r_k = 1$, $\beta = 2$, and $\phi = 0$.

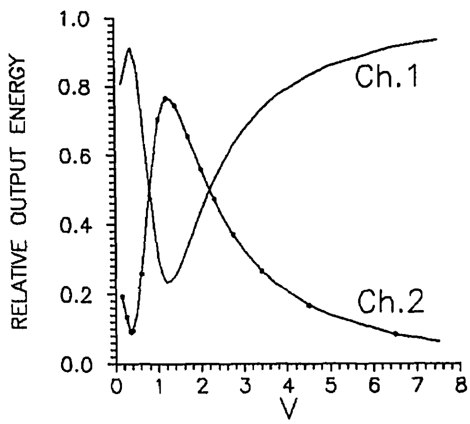

Fig. 2. Relative output probe energies channels 1 and 2 after the soliton collision as a function of the collision angle. Other parameters are the same as in Fig. 1.

collide, producing an interaction pattern, but then they emerge unchanged. On the other hand, Fig. 1(b) shows the evolution of the probe beam. At the beginning, the probe beam is simply guided by the right soliton optical channel. However, it meets the soliton interaction region and splits its energy into the two emerging soliton channels (channels 1 and 2). Physically, the probe-beam energy splitting occurs because the beam passes through an effective phase diffraction grating formed by the soliton interference pattern.

Figure 2 shows the relative output energies in each channel after the soliton collision as a function of the initial angular separation, $v = \tan(\theta)$. For large values of v, almost all the output probe-beam energy remains in the original optical channel. However, as v decreases, it is possible to switch a considerable fraction of the input probe-beam energy into the other optical channel. For the specific parameters used in Fig. 1, the special symmetric optical Y junction occurs for either $v \approx 0.8$ or $v \approx 2.2$, and it can be considered the bright-soliton equivalent of the Y junction reported in Ref. 3.

Figure 3 characterizes the splitting properties of the optical Y junction as a function of the relative initial phase difference of the two solitons ϕ. As can be seen, a more nearly perfect switching from the input channel to the other channel can be obtained for $v \approx 0.375$, where the transmission (channel 1 of Fig. 2) has a maximum. In this particular case, complete switching is predicted for $\phi = 0.6\pi$.

As we stated above, an analytical description of the splitting of the probe beam during a channel crossing of two bright spatial solitons resides in the diffraction of the probe beam by a phase diffraction grating formed by the soliton collision pattern. Naturally, the profile of such a diffraction grating varies with the distance Z, and an exact description is not simple. However, most of the characteristic features exhibited in Figs. 2 and 3 can be well described if we assume a phase diffraction grating with a central soliton collision profile, i.e., Eq. (3) with $c = 0$, and with a thickness equal to the length of the collision region, which is estimated to be $h = 2/v$. This means that we must consider a diffraction grating, given by the transfer function

$$\begin{aligned} T(X) &= \exp(-ih\Psi) \\ &= \exp[-i4h\beta\, \mathrm{sech}^2(X)\cos^2(vX + \phi/2)]. \end{aligned} \tag{4}$$

The probe beam at the output of the phase diffraction grating is $A_d(X) = A_2(X, 0)T(X)$, and its angular spectrum is given by

$$\tilde{A}_d(k_x) = \int_{-\infty}^{\infty} \exp(-ih\Psi)\mathrm{sech}(X)\exp[-i(k_x - v)X]\mathrm{d}X\,. \tag{5}$$

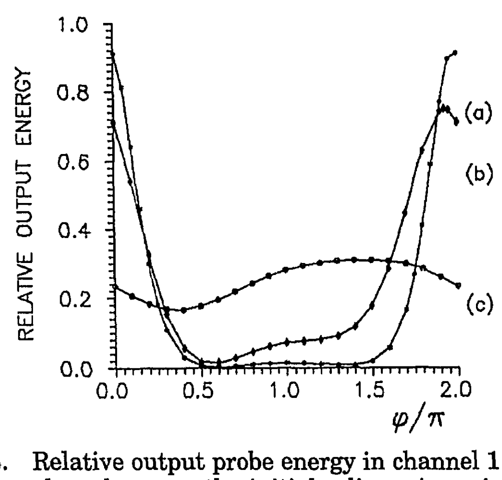

Fig. 3. Relative output probe energy in channel 1 as the relative phase between the initial solitons is varied: (a) $v = 0.375$, (b) $v = 0.625$, (c) $v = 1.25$. Other parameters are the same as in Fig. 1.

It is not possible, to our knowledge, to express the result of such integration in terms of elementary functions for arbitrary h. However, it is possible to get some insight into the behavior of $\tilde{A}_d(k_x)$ for two physically interesting cases: large and small collision angles. Large values of v mean small values of h, and this permits the series expansion of the transfer function $T(X)$. Expanding the exponential function of Eq. (4) up to the first order in h and performing the integration in Eq. (5), we obtain

$$\tilde{A}_d(k_x) = \sum_{l=0}^{2}(B_l - D_l)\mathrm{sech}\{\pi[k_x + (2l - 3)v]/2\}, \quad (6)$$

where $B_l = 1 - |l - 1|$ and $D_l = ih\beta \exp[i(1 - l)\phi](1 - |l - 1|/2)\{1 + [k_x + (2l - 3)v]^2\}$. Equation (6) establishes that for large collision angles the spectrum of the scattered probe beam possesses components at the initial (channel 1) and the other (channel 2) soliton channels. Therefore, taking the ratio of the peak intensity of the $k_x = -v$ component to that of the $k_x = v$ component, we estimate the normalized output energy guided by channel 2 after the soliton collision to be $\beta/(v^2 + 4\beta^2)$. This result describes with high accuracy the numerical results depicted in Fig. 2 for large values of v. Also, it is worth noting that when large collision angles are used Eq. (6) does not predict any substantial effect of the initial soliton phase difference ϕ on the output probe beam energies. This fact agrees with Fig. 3, in which the switching properties of the Y junction, as ϕ is varied, are lost for increasing v.

On the other hand, for small collision angles the grating becomes thick ($h \gg 1$) and the transfer function $T(X)$ oscillates rapidly. Therefore, after the grating, the channel 1 probe-beam spectrum, $\tilde{A}_d(v)$, can be evaluated from Eq. (5) with the method of stationary phase.[9] The main contributions are due to the points x_i at which $\partial\Psi/\partial X = 0$, and from Eq. (4) they satisfy the trascendental equation $\tanh(x_i) = -v\tan(vx_i + \phi/2)$. Assuming that $\phi = 0$ and $k_x = v$, with $x_1 = 0$, we obtain

$$\tilde{A}_d(v) \approx \exp(-i4h\beta)[\pi v/8\beta(1 + v^2)]^{1/2}. \quad (7)$$

This result indicates that the peak spectral intensity at $k_x = v$ is proportional to $v/(1 + v^2)$, and it qualitatively describes the behavior of the output probe energy in the original channel depicted in Fig. 1 for $v < 1$. A more-detailed description will require the consideration of the whole spectral distribution of the output probe beam. The presence of ϕ shifts the points x_i and modifies the result of relation (7). This explains the switching behavior observed in Fig. 3.

Our numerical simulations show that one can address the issue of the probe beam and the soliton wavelength sensitivity by looking at the oscillatory and final monotonic parts of Fig. 2. For $\beta < 2$ ($\lambda_1 < \lambda_2$), the former diminishes, reducing the switching capability of the soliton crossing described in Fig. 3. A detailed analysis of the possible applications of this junction as a wavelength-discriminating switch is the subject of our continuing research.

Finally, these results should be generalized to cases of optical junctions formed by the collision of three or more bright spatial solitons in self-focusing media. It is also possible to obtain an extension to optical fibers when two colliding solitons are coupled to a probe pulse of different wavelength through the cross-phase-modulation effect.

In summary, we have shown that a collision of two bright spatial solitons can be used to obtain controllable optical Y junctions in self-focusing media. The splitting of an input probe beam into the two soliton optical channels emerging from the collision is due to the scattering of the probe beam by the phase grating induced in the region of soliton crossing. The characteristic of such an optical junction can be varied by changing the interference pattern. The practical realization of these junctions requires the consideration of nonlinear material long enough to include the experimental length of the junctions. To distinguish the output channels requires several diffraction lengths, $L_{\mathrm{diff}} = n_0k_0x_0^2$, and this favors smaller beam widths x_0.

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