Ultrafast deflection of spatial solitons in $Al_xGa_{1-x}As$ slab waveguides

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We demonstrate ultrafast all-optical deflection of spatial solitons in an $Al_xGa_{1-x}As$ slab waveguide, using 190 fs, 1550 nm pulses to generate and deflect the spatial soliton. The steering beam is focused onto the top of the waveguide near the soliton pathway, and the soliton is steered by refractive-index changes induced by optical Kerr, or free-carrier (Drude), effects. Angular deflections up to 8 mrad are observed. © 2005 Optical Society of America

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Optical spatial solitons are shape-invariant wave packets maintained by the balancing of linear and nonlinear optical effects. The nonlinear processes that compensate for diffraction and produce guiding can be induced by, e.g., an intensity-dependent refractive index (Kerr effect), photorefractive effects, or cascaded second-order optical nonlinearities.[1] While interesting objects of study in themselves, solitons are also being considered for information-processing applications such as optically reconfigurable logic devices.[2] The switching of spatial solitons is an essential process for many applications, and popular embodiments include nonlinear interactions of copropagating spatial solitons[3,4] and electro-optically induced pathway distortions. All-optical ultrafast reconfiguration of soliton pathways, e.g., as a result of the Kerr effect, in the telecommunication wavelength regime (1.3–1.6 μm) is an attractive goal and offers higher switching speeds than electro-optic methods. However, besides the copropagating schemes one should consider other techniques that have been discussed in the more general realm of light-by-light switching, such as optically or electro-optically induced birefringence[5,6] and optically induced prisms[7] or gratings.[8]

Here we demonstrate an ultrafast, nonplanar switching scheme for spatial solitons formed in a 2D $Al_xGa_{1-x}As$ waveguiding layer by inducing a localized refractive-index perturbation in the spatial soliton pathway, using femtosecond light pulses normally incident upon the waveguide. The general principle of the technique is depicted in Fig. 1 which shows an optical soliton formed at the entrance facet of a (2D) waveguide by an ultrashort laser pulse. A separate ultrashort pump pulse is focused onto the top of the waveguide, introducing an index change Δn in the waveguiding layer with the spatial profile of the pump pulse. Δn, which can be generated on either side of the spatial soliton pathway, causes the soliton to deflect while it remains intact: The robust nature of soliton propagation means that it is not necessary to form an optically induced prism of a particular shape.[9] The deflection direction also depends on the sign of Δn, which is >0 for the optical Kerr effect and <0 for any free-carrier (Drude-) induced index change in $Al_xGa_{1-x}As$. For $\Delta n>0$ the soliton path bends toward the index gradient, whereas for $\Delta n<0$ deflection occurs in the opposite direction. Temporal control of the deflection is achieved by delaying the soliton-forming pulse with respect to the pump pulse; temporal resolution is related to the convolution of both pulses.

The waveguide structure that we employ consists of a 1.5 μm thick, 10 mm long (in the $\langle 110\rangle$ direction) $Al_xGa_{1-x}As$ waveguiding layer ($x=0.18$; bandgap, 1.64 eV$\equiv$756 nm) sandwiched between a 4 μm thick lower and a 1.5 μm thick upper cladding, both with $x=0.24$. The pulses used to generate and steer the solitons are obtained from an ultrafast laser system: a 250 kHz optical parametric amplifier producing 190 fs pulses, centered at $\lambda=1550$ nm (photon energy, 0.8 eV). For soliton formation a 1.4 kW peak power pulse is elliptically shaped by a cylindrical telescope (to facilitate good coupling into the waveguide) and subsequently passed through an 11 mm focal-length

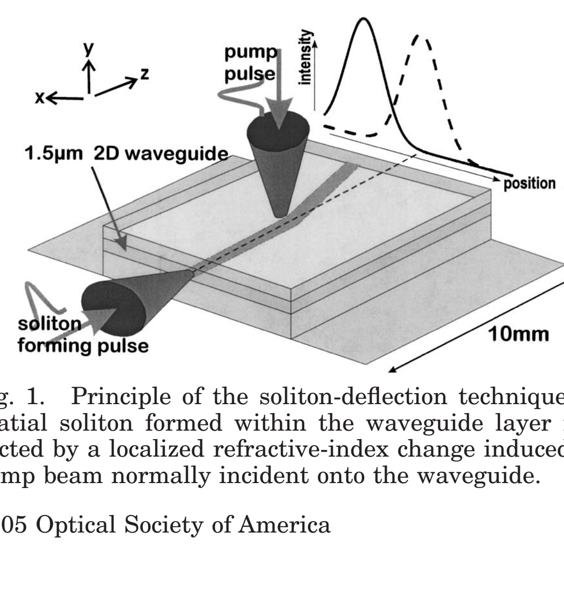

Fig. 1. Principle of the soliton-deflection technique: The spatial soliton formed within the waveguide layer is deflected by a localized refractive-index change induced by a pump beam normally incident onto the waveguide.

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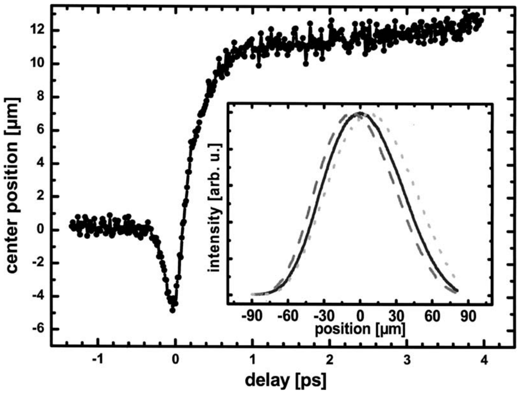

Fig. 2. Center position of the soliton intensity distribution emerging from the exit facet versus the time delay, Δt, between the soliton-forming and pump ultrashort laser pulses. Inset, the intensity profiles at the exit facet at $\Delta t = -1$ ps (solid curve), $\Delta t = 0$ (dashed curve), and $\Delta t = 3$ ps (dotted curve).

lens to produce an appropriate lateral width at the waveguide. The in-plane intensity diameter is $\approx 28\ \mu$m (measured at e^{-1} points) at the entrance facet with the light polarized in plane. We observe that the soliton maintains its width for $>3\times$ the linear diffraction length; it has a width of $\approx 80\ \mu$m at the exit facet. The pump or steering pulse has a peak power of 220 kW and is focused to a diameter (at e^{-1} points) of $\approx 19\ \mu$m polarized parallel to the soliton polarization. The peak intensity is a factor of 5 below the damage threshold. For maximal deflection the center of the pump pulse focus is located 0.5 mm from the entrance facet and is displaced laterally from the soliton channel such that the soliton experiences the largest lateral variation in the induced refractive index (see below). The time delay, Δt, between the soliton and the pump pulse is controlled with a delay stage.

Figure 2 shows the change in the center of the soliton lateral intensity distribution at the exit facet, as a function of Δt. The fast, pulse-width-limited deflection toward the pump beam position near $\Delta t = 0$ is attributed to the third-order nonlinear optical response, the optical Kerr effect, and peaks at $\approx 4.6\ \mu$m. For an estimated peak focused intensity $I_0 = 75\ \mathrm{GW\,cm^{-2}}$ and a Kerr coefficient of[10] $n_2(1550\ \mathrm{nm}) = 1.4\times 10^{-4}\ \mathrm{cm^2\,GW^{-1}}$, we estimate a peak refractive-index change of $n_2 I_0 = 0.01$. However, for Δt larger than the temporal pulse width the deflection reverses, bends away from the pump location, and achieves a maximum value of $>12\ \mu$m owing to the refractive-index change induced by free carriers. For even higher intensities, obtained by tighter focusing of the pump beam and yielding higher carrier densities, deflections of up to $80\ \mu$m have been achieved, corresponding to a deflection angle of 8 mrad; this is larger than the soliton diameter by more than a factor of 2. The Drude-based change in the refractive index by free carriers of density N is most likely due to three-photon absorption; two-photon absorption is not energetically allowed. Indeed, from Wherrett's scaling laws[10,11] for multiphoton absorption we estimate a three-photon absorption coefficient of $0.05\ \mathrm{cm^3\,GW^{-2}}$, so the injected carrier density is estimated to be $N = 3\times 10^{18}\ \mathrm{cm^{-3}}$. From the refractive-index change with carrier density[12] $\mathrm{d}n/\mathrm{d}N \equiv \sigma_n = -7.4\times 10^{-21}\ \mathrm{cm^3}$ for 1550 nm, we obtain a peak refractive-index change of $\sigma_n N = -0.02$.

Figure 3 shows how the Kerr-induced and carrier-induced deflection amplitudes scale with focused pump intensity I_0. As expected, the former scales linearly with I_0, consistent with a Kerr effect, while the latter scales as $I_0^{\,3}$ in accord with three-photon absorption or a cascaded three-photon absorption process. The carrier-induced response rises on a time scale related to the pulse width, although it might be noted that there is a slow (1 ps rise time) component, which we attribute to cooling of the carriers, perhaps also involving intervalley scattering, with the effective mass of conduction band electrons decreasing and enhancing the Drude contribution to the refractive-index change. The carrier-induced response remains for the carrier lifetime, which is of the order of several hundred picoseconds for our sample. With appropriate engineering the recombination time could be reduced or carrier-induced changes could be enhanced. Alternatively, carrier responses can be avoided by working with lower peak intensity, e.g., by using a larger focal area. The maximum deflection is then limited by the pump pulse energy and the temporal pulse width. Note that, with the present experiments, the onset of the carrier-induced refractive-index change partly masks the Kerr effect, and the actual Kerr-induced deflection in Fig. 2 is likely to be much larger than the $4.6\ \mu$m indicated.

A simple estimate of the observed deflection for refractive-index changes that are due to the optical Kerr effect $[\Delta n(I) = n_2 I]$ can be given as follows: Consider a planar slab waveguide contained along the y direction with light propagating in the z direction, as indicated in Fig. 1. The nonlinear wave equation is

$$\frac{\partial^2 A(x,z)}{\partial x^2} + \frac{n_2}{\eta_0} k^2 |A(x,z)|^2 A(x,z) = 2ik \frac{\partial A(x,z)}{\partial z}, \quad (1)$$

with $\eta_0 = n_0 c \epsilon_0 / 2 \approx 4.3\times 10^{-3}$, where $n_0 = 3.24$ is the refractive index of the slab and $k = n_0 2\pi/\lambda$. The solution to Eq. (1) is

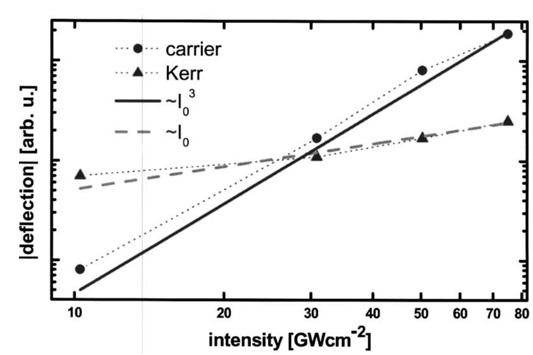

Fig. 3. Scaling of Kerr- and carrier-induced deflection magnitude measured with a position-sensitive device.

$$A(x,z) = A_0 \operatorname{sech}\left(\frac{x}{W_0}\right)\exp\left(-i\frac{z}{2kW_0{}^2}\right), \qquad (2)$$

where $A_0=\sqrt{2\eta_0/n_2}/(kW_0)$ is the amplitude of the so-called bright soliton and W_0 is its width. A Kerr-induced change in the refractive index along the x direction, with the ultrafast pump and soliton pulses overlapping in time, in addition to the one already induced by the soliton itself leads to a spatially dependent phase shift for the propagating soliton and therefore to a refraction toward the direction of the gradient of the phase shift. The index variation induced by a pulse focused onto the waveguide is taken to be of the form $\Delta n(x,z)=n_2 I(x,y)=n_2 I_0 \exp\{-[(x-x_0)^2+z^2]/w_0{}^2\}$, where I_0 is the peak intensity of the focused pump beam, w_0 is its width, and $(x_0,z=0)$ is the center of the focal spot. If the focused beam is located such that $\partial^2 I/\partial x^2=0$ at the center of the soliton (i.e., for $x_0=w_0/\sqrt{2}$), and if we assume that $w_0 \gtrsim 2W_0$, to a first approximation a linear phase differential $\phi(x,z)$ is induced in the soliton between $x_0=\pm w_0/\sqrt{2}$, with

$$\frac{\partial\phi(x,z)}{\partial x} \propto \frac{2\pi}{\lambda}\left.\frac{\partial n}{\partial x}\right|_{x_0} = \frac{2\pi}{\lambda}\sqrt{\frac{2}{e}}\frac{n_2 I_0}{w_0}\exp\left[-\frac{(z-z_0)^2}{w_0{}^2}\right]. \qquad (3)$$

In general, a soliton traveling through the waveguide at a small angle $\theta(\approx \sin\theta)$ with respect to the z direction can be described by[13]

$$A(x,z) = A_0 \operatorname{sech}\left(\frac{x-\theta z}{W_0}\right) \times \exp\left(-iz\frac{1-k^2 k W_0{}^2\theta^2}{2kW_0{}^2} - ixk\theta\right), \qquad (4)$$

which is equivalent to the solution in Eq. (2) at the place of deflection ($z=0$) multiplied by a phase factor $\exp(-ixk\theta)$. The phase differential ϕ can be related to the generic phase shift $xk\theta$ at $z=0$ through

$$\int_{-W_0}^{W_0} k\theta \mathrm{d}x = 2W_0 k\theta \qquad (5)$$

$$\equiv \int_{-\infty}^{\infty}\frac{\partial\phi(x,z)}{\partial x}\mathrm{d}z = \frac{(2\pi)^{3/2}}{\lambda e^{1/2}} n_2 I_0 w_0. \qquad (6)$$

This gives a deflection angle of

$$\theta \approx \frac{1}{2}\left(\frac{2\pi}{e}\right)^{1/2}\frac{w_0}{W_0}\frac{n_2 I_0}{n_0}. \qquad (7)$$

With $w_0 \approx 2\times W_0$ and $I_0 \approx 75\ \mathrm{GW\,cm^{-2}}$, relation (7) gives $\theta \approx 2.5$ mrad. This is within a factor of 3 of the observed Kerr-induced deflection angle of ~ 1 mrad, although the Drude effect partially obscures the Kerr effect. The deflection angles reported here are comparable to those achieved with switching techniques that involve copropagating solitons and electrically induced prisms, although the interaction lengths in the latter cases are much longer.[4,14]

In summary, we have demonstrated the feasibility of all-optical alteration of the pathways of spatial solitons in two-dimensional semiconductor waveguides on an ultrafast time scale, employing the optical Kerr nonlinearity of the medium. The deflection scheme reported here does not require a precise geometrical form for the refractive-index change. It also offers complementary degrees of freedom to the copropagating soliton-switching scheme. In addition, we have observed Drude-induced deflection of spatial solitons. The ultrafast temporal nature and particular geometry of the deflection technique enable one to write and perform information processing applications by using spatial solitons, with the maximum deflection angle limited only by the maximum possible phase shift across the soliton. Merging the capabilities of the approach described here with the scheme of optical interconnects[14] makes additional applications possible.

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