Optical switching using nonlinear polarization rotation inside silicon waveguides

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We study the nonlinear polarization rotation induced by a pump pulse on a probe beam through cross-phase modulation inside a silicon waveguide and show that this phenomenon can be used to realize a fast Kerr shutter in spite of the free-carrier effects and walk-off. We show that free carriers generated by the pump pulse through two-photon absorption affect the switching process considerably, especially with the interaction of walk-off effects. However, numerical simulations reveal that their impact is not detrimental for short pump pulses. In this case, an approximate analytical solution predicts the shape and duration of the switching window with reasonable accuracy. © 2009 Optical Society of America

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In recent years, nonlinear effects in silicon-on-insulator (SOI) waveguides are attracting attention because of their tight-mode confinement and a relatively high Kerr nonlinearity [1]. All-optical switches based on such waveguides are an important component for any integrated optical circuit. Although several switching schemes have been explored in the past [2–5], a Kerr shutter [6] has not yet been realized. In this Letter we propose and analyze optical switching in an SOI waveguide through nonlinear polarization rotation (NPR) induced by cross-phase modulation (XPM). Two-photon absorption (TPA), free carriers, and linear birefringence affect the device operation but are not detrimental for such an optical switch under optimum operating conditions.

The basic idea behind a Kerr switch is to change the state of polarization of a probe beam inside an SOI waveguide by utilizing nonlinear changes in the refractive index that are produced by an intense pump pulse (NPR through XPM). A polarizer at the output end of the waveguide transmits the probe only when a pump pulse is present, thus converting the waveguide into an optical switch.

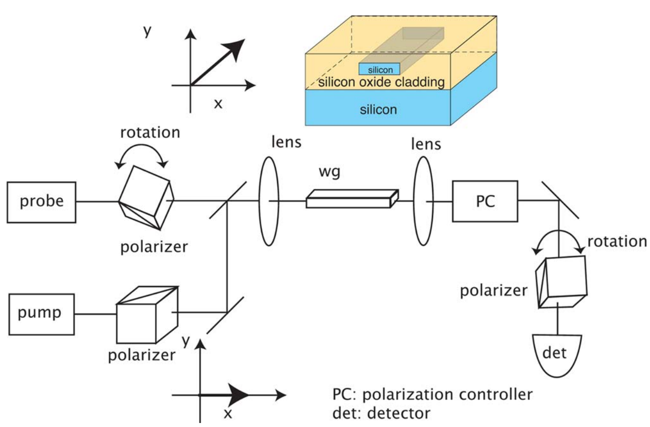

Fig. 1. (Color online) Schematic setup of the proposed optical Kerr shutter; waveguide geometry is shown on the top.

We adopt the configuration shown in Fig. 1 for our Kerr switch. Pump pulses are polarized along the x axis and propagate as a semi-TE mode. The cw probe, polarized at 45° with respect to the pump, excites both TE and TM modes equally. The phases of the two probe components change through XPM by different amounts, resulting in a net relative phase shift that manifests as NPR. We calculate this phase shift by solving three coupled equations [7]:

$$\frac{\partial E_x}{\partial z} + d_x \frac{\partial E_x}{\partial T} = 2ik_0 n_2 a(1+ir)I_p E_x - \frac{\sigma}{2}(1+i\mu)N_c E_x - \alpha_l E_x/2 + i(\beta_x - \bar{\beta})E_x, \quad (1)$$

$$\frac{\partial E_y}{\partial z} + d_y \frac{\partial E_y}{\partial T} = 2ik_0 n_2 b(1+ir)I_p E_y - \frac{\sigma}{2}(1+i\mu)N_c E_y - \alpha_l E_y/2 + i(\beta_y - \bar{\beta})E_y, \quad (2)$$

$$\frac{\partial I_p}{\partial z} = -\beta_{\mathrm{TPA}} I_p^2 - \sigma N_c I_p - \alpha_l I_p, \quad (3)$$

where E_x and E_y are the probe amplitudes and $I_p = |E_p|^2$ is the pump intensity. Only the intensity equation is needed for the pump, because its phase does not affect the XPM process. The cw probe is assumed to be so weak that it does not induce any nonlinear effects. The pump-induced XPM effect is included through the Kerr parameter n_2. The coefficients a and b indicate that the strength of XPM depends on the relative polarizations of the pump and probe. In the case of silicon, $a=(1+\rho)/2$ and $b=\rho/3$, where the anisotropic factor $\rho \approx 1.27$ [1]. The TPA of the pump is governed by $r=\beta_{\mathrm{TPA}}/(2k_0 n_2)$. The free carriers absorb both the pump and probe light, and σ governs the magnitude of this absorption. Equally important is the index change induced by free carriers whose magnitude is controlled by μ. The linear losses are taken to be the same for the pump and probe, although they may differ in some situations. The last term in the probe equations accounts for the birefringence resulting from different mode indices n_x and n_y for the TE and TM modes. Here, $\bar{\beta}=(\beta_x+\beta_y)/2$ is the average value of $\beta_x=n_x k_0$ and $\beta_y=n_y k_0$, with $k_0=2\pi/\lambda_s$, λ_s being the probe wavelength. The walk-off effects result from different group velocities of the pump and probe components. Since only relative speeds matter, we work in a frame moving at the pump speed and introduce a reduced time $T=t-z/v_{gp}$. Using the notation, $\beta_{1j}=\mathrm{d}\beta_j/\mathrm{d}\omega=1/v_{gj}$ with $j=x,y,p$, the two walk-off parameters of the probe are defined as $d_x=\beta_{1x}-\beta_{1p}$ and $d_y=\beta_{1y}-\beta_{1p}$. Finally, the carrier density $N_c(z,T)$ evolves as

$$\frac{\partial N_c}{\partial T}=\frac{\beta_{\mathrm{TPA}}}{2h\nu_p}I_p^2(z,T)-\frac{N_c}{\tau_c}, \tag{4}$$

where $h\nu_p$ is the energy of a pump photon and τ_c is the carrier lifetime. To be consistent, we have neglected the terms containing probe intensity, assuming a relatively weak probe.

A numerical solution of Eqs. (1)–(4) provides a reasonable description of the pump-induced NPR effects. Before discussing the numerical results, we show that an approximate analytic solution is also possible and can provide considerable physical insight. The simplifying approximation is that free-carrier effects are negligible. This approximation is too drastic to be valid in general. However, we show later that it is reasonable for relatively short, not too intense, pump pulses that are widely separated. Since the pump equation (3) does not depend on the probe, it can be solved easily when $N_c=0$:

$$I_p(z,T)=\frac{\alpha_l I_0(T)e^{-\alpha_l z}}{\alpha_l+\beta_{\mathrm{TPA}}I_0(T)(1-e^{-\alpha_l z})}, \tag{5}$$

where $I_0(T)$ is the intensity profile of the input pulse launched at $z=0$. The two probe equations can also be solved analytically because of their linear nature. Introducing $T_x'=T-d_x z$ and the transformation $E_x=A_x e^{-\alpha_l z/2}e^{i(\beta_x-\bar{\beta})z}e^{i\phi_x}$, Eq. (1) leads to

$$\frac{\partial A_x}{\partial z}=-2k_0 n_2 a r I_p A_x, \quad \frac{\partial \phi_x}{\partial z}=2k_0 n_2 a I_p. \tag{6}$$

Both of them can be solved to obtain

$$A_x(z,T_x')=A_x(0,T_x')\times\exp\left[-a\int_0^z \times\frac{\alpha_l e^{-\alpha_l z'}\beta_{\mathrm{TPA}}I_p(0,T_x'+d_x z')}{\alpha_l+\beta_{\mathrm{TPA}}I_p(0,T_x'+d_x z')(1-e^{-\alpha_l z'})}\mathrm{d}z'\right], \tag{7}$$

$$\phi_x(z,T_x')=\frac{a}{r}\int_0^z \frac{\alpha_l e^{-\alpha_l z'}\beta_{\mathrm{TPA}}I_p(0,T_x'+d_x z')}{\alpha_l+\beta_{\mathrm{TPA}}I_p(0,T_x'+d_x z')(1-e^{-\alpha_l z'})}\mathrm{d}z'. \tag{8}$$

The solution for A_y is obtained by replacing a with b and the subscript x with y in Eqs. (7) and (8).

The NPR of the probe beam by the pump beam is governed by the relative phase shift $\Delta\phi=\phi_x-\phi_y$. Notice that the linear birefringence of the waveguide also leads to a phase difference between the two polarization components. This birefringence-induced polarization rotation can be compensated by using a polarization compensator after the waveguide. Another polarizer is needed after the polarization compensator to block the probe in the absence of a pump pulse. Each pump pulse changes probe polarization through NPR such that some probe light is transmitted through the polarizer over the pump duration.

To test the range of validity of the analytic solution, we have solved Eqs. (1)–(4) numerically for a 5-mm-long SOI waveguide with a cross-section area of $600\times450\ \mathrm{nm}^2$. The pump and probe wavelengths are $\lambda_p=1.56\ \mu\mathrm{m}$ and $\lambda_s=1.54\ \mu\mathrm{m}$. The walk-off parameters are calculated using the dispersion curves for the fundamental TE and TM modes and are $d_x=-0.78$ ps/cm and $d_y=30.2$ ps/cm. For the nonlinear parameters, we use the values from our recent measurements [8]: $n_2=2.5\times10^{-18}\ \mathrm{m}^2/\mathrm{W}$, $\beta_{\mathrm{TPA}}=5\times10^{-12}$ m/W. We note that n_2 values in the literature differ by up to a factor of 2, but our results are not too sensitive to the exact value if the device length is adjusted to obtain the same nonlinear phase shift. The other parameters are chosen to be $\sigma=1.45\times10^{-21}\ \mathrm{m}^2$, $\mu=7.597$ [7], $\tau_c=1.5$ ns, $\alpha_l=5$ dB/cm, and $A_{\mathrm{eff}}=0.1\ \mu\mathrm{m}^2$. The peak power is 4 W for the sech pump pulses with $P_p(T)=P_0\,\mathrm{sech}(T/T_0)^2$. The width T_0 is varied over a wide range to study the shape and duration of the NPR-induced switching window. The input power of the weak cw probe is 1 mW.

Figure 2 compares the switching windows for values of T_0 ranging from 1 ns to as short as 0.1 ps obtained numerically (thin curves) with those predicted analytically (thick curves) by neglecting the free-carrier effects. These results show that free carriers play a significant role for pulses much wider than 1 ps but can be neglected for shorter pump pulses. In particular, the switching window is not affected much by free carriers for 100 fs pulses. In the case of 1 ps pump pulses, the switching windows almost coincide except for a low-amplitude tail that results from the interaction between the free-carrier effects and the walk-off effect. Free-carrier effects break the temporal symmetry of the probe field. In the presence of group-velocity mismatch, the free-carrier-induced phase shift is not the same for A_x and A_y, resulting in polarization changes that produce some leakage of the probe power. With this in mind, we can understand the appearance of a second peak for 10 ps or wider pulses. Since the index and phase changes produced by the XPM and free carriers occur with opposite signs, they cancel each other occasionally. The

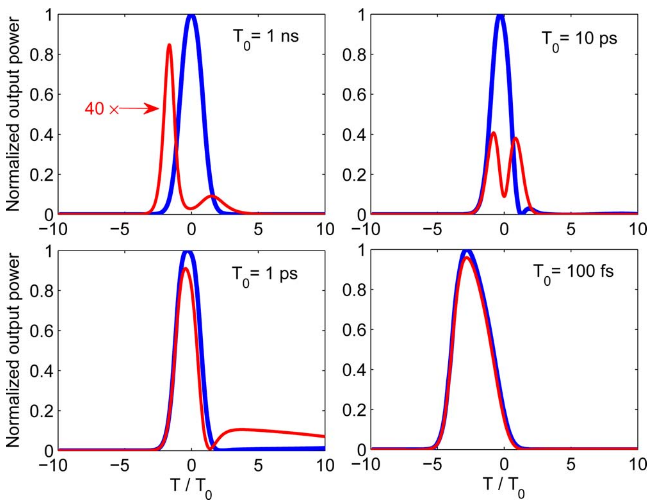

Fig. 2. (Color online) Switching windows for four different pump-pulse widths. The thinner (red) curves mark the numerical results, while the thicker (blue) curves show the analytical prediction neglecting the free-carrier effects.

case of very long pulses ($T_0 > 100$ ps) is interesting, because the switching window can be considerably shorter than the pump pulse but at the expense of a much-reduced power (note the magnification by a factor of 40, in Fig. 2 for this case).

We note from Fig. 2 that the performance of a silicon-based Kerr shutter suffers considerably (compared with the case of silica fibers) from a combination of the free-carrier and walk-off effects. The use of a square-shape waveguide may help because it will reduce the birefringence effects. Figure 3 shows the results under conditions identical to those of Fig. 2, except that a square-shape waveguide (450×450 nm^2) is employed with the modified values $d_x = -1.98$ ps/cm, $d_y = -1.16$ ps/cm, and $A_{\text{eff}} = 0.09$ μm^2. As expected, the switch performance is improved considerably because of reduced walk-off effects. In particular, the long tail seen in Fig. 2 for 1 ps pump pulses has disappeared completely. We should point out that the performance of a Kerr switch also depends on the peak power of pump pulses. In the case of Kerr shutter based on silica, one may want to choose the power level such that $\Delta\phi \approx \pi$. However in the case of silicon waveguides, nonlinear absorptions set the limit on peak pump power. Serious distortion on switching window starts even before $\Delta\phi$ approaches π.

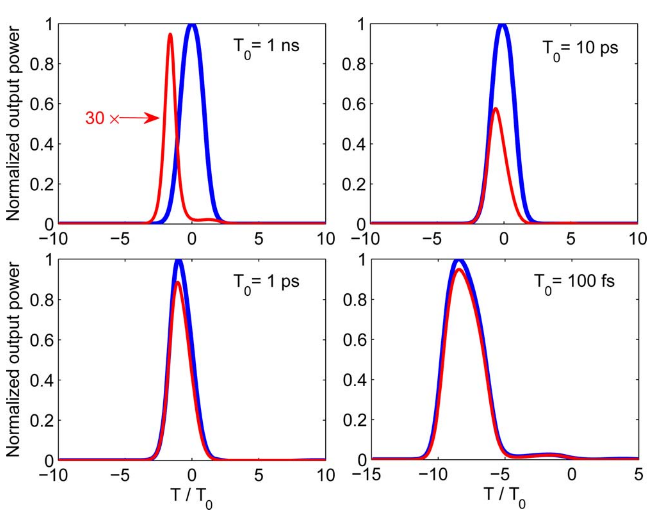

Fig. 3. (Color online) Switching windows for the same four pump-pulse widths and the same operating conditions used in Fig 2. The only difference is that a square-shape silicon waveguide is employed to minimize walk-off effects.

In conclusion, we have shown theoretically that the NPR, induced by a pump pulse on a cw probe inside a silicon waveguide, can be used to realize a fast Kerr shutter. We show that free carriers generated by the pump pulse through TPA affect the switching process because of a combination of the free-carrier and walk-off effects. However, their impact is not detrimental for pump pulses shorter than 5 ps or so, especially when birefringence effects are minimized by employing a square-shape waveguide. For such short pulses, an approximate analytical solution predicts the shape and duration of the switching window with reasonable accuracy. Even though a switching window of <5 ps duration can be realized using SOI waveguides, we stress that the repetition rate of such a switch is invariably limited by the carrier lifetime. It is unlikely to exceed 1 GHz unless the effective carrier lifetime is reduced substantially using a suitable technique such as carrier sweeping by an external electric field [9] or enhanced recombination through ion implantation [10].

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