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Ultrafast all-optical switching in AlGaAs photonic crystal waveguide interferometers

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We have demonstrated ultrafast all-optical switching with photonic crystals integrated into AlGaAs Mach–Zehnder interferometers. The nonlinearity is induced by optical excitation of carriers into one arm of the interferometer, and switching times as short as 3 ps are achieved by surface recombination at the air holes in the photonic crystal. The fast recombination times and high nonlinearities of the AlGaAs material make this design suitable for high speed all-optical switching applications. © *2009 American Institute of Physics*. [doi:10.1063/1.3236542]

It is projected that telecommunication bandwidths of $\sim$100 Gbit/s will be required in the near future, and it is likely that all-optical switching components will be needed to meet this demand. These all-optical devices are not limited by the *RC* time constants that affect electro-optic components, and hence potentially offer higher network speeds. However, much progress is still required to fulfill this promise. In particular, high signal-to-noise ratios and fast switching speeds need to be combined with low power consumption. In this context, photonic crystals (PhCs) offer many interesting possibilities.[1–5] In particular, III-V PhCs feature short carrier lifetimes due to increased surface recombination[6–9] and also the prospects for slow light enhanced optical switching.[10,11]

In a previous work on carrier-induced switching in silicon PhCs, the switching speed was limited by the carrier lifetime, which is in the range of a few tens of picoseconds at best.[12] Faster switching has been obtained in quantum dot devices by using a set and reset operation,[13] but the maximum bit-rate was still limited by a much longer carrier lifetime. It is therefore clear that a very short carrier lifetime is essential. In this letter, we demonstrate ultrafast all-optical switching in AlGaAs Mach–Zehnder interferometer (MZI) devices. The compact Mach–Zehnder geometry enables us to exploit the free carrier nonlinearity in an efficient way, and the fast switching speeds are achieved by combining the high diffusivity of the carriers in the III-V material with the rapid surface recombination at the etched sidewalls of the PhC. By comparing a variety of PhC geometries, we have been able to achieve switching times as short as 3 ps, which confirms the excellent potential of III-V PhC waveguides for ultrafast all-optical switching.

The MZI devices consisted of two symmetric waveguide arms with 50:50 power splitters at each end, as shown in Fig. 1(a). With a single probe beam incident at the input port, the output is given by the two-beam interference equation

$$I = (I_1 + I_2 + 2\sqrt{I_1 I_2}\cos \Delta\phi)/2, \tag{1}$$

where I_1 and I_2 are the intensities in the two arms and $\Delta\phi$ is the phase difference. In our experiments a pump beam generated free carriers in arm 1, thereby changing I_1 through induced absorption or $\Delta\phi$ through nonlinear refraction. In either case, the interferometer transmission changes, leading to a nonlinear signal at the output.

The interferometers were fabricated in an AlGaAs waveguide wafer grown on a GaAs substrate by metal-organic vapor phase epitaxy. The waveguide consisted of an $Al_{0.2}Ga_{0.8}As$ core of thickness 400 nm with air as the top cladding and an $Al_{0.6}Ga_{0.4}As$ layer of thickness 1500 nm as the lower cladding. The interferometers were patterned onto the top surface of the wafer by electron-beam lithography and were then etched by chemically assisted ion-beam etching. Multimode interference (MMI) couplers were used as the 3 dB power splitters. The MMI width was 6 μm, which resulted in a 64 μm optimum splitting length,[14] and a measured optical bandwidth of at least 60 nm. S-bend

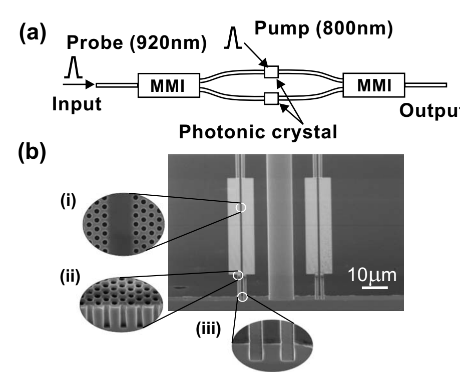

FIG. 1. (a) Schematic of the MZI switch. The total length of the MZI excluding the PhC waveguides was 480 μm, and the input and output waveguides had a width of 1.5 μm. The W1 and W3 PhC waveguides had a length L of $130\times a$, where a is the lattice constant, giving L=36 and 46 μm, respectively. The value of L was reduced to 12.6 μm (i.e., $50\times a$) for the self-collimator. (b) Scanning electron micrograph (SEM) of the W3 PhC waveguides. The three zoomed SEMs show, respectively, (i) the W3 waveguide, (ii) the verticality of the PhC holes, and (iii) the sidewalls of the ridge waveguide.

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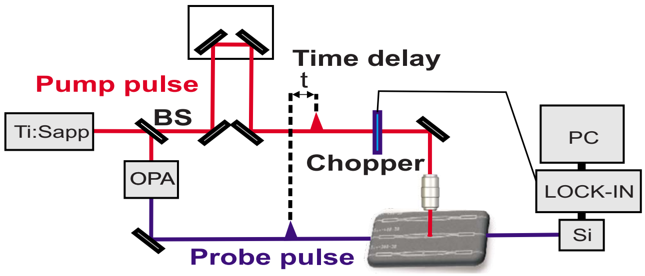

FIG. 2. (Color online) Experimental setup.

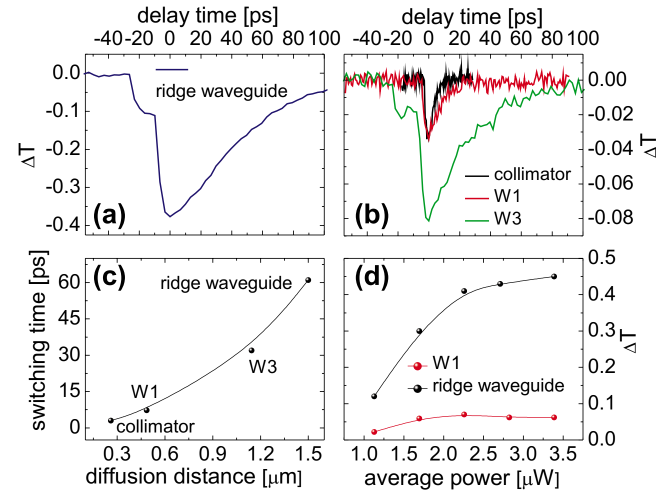

FIG. 3. (Color online) Time dependence of the nonlinear transmission spectra for (a) the ridge waveguide reference sample and (b) the three different types of PhC design. The probe light wavelength was 920 nm for each sample. The signal at ~−20 ps for the W3 and ridge waveguide interferometers is caused by a reflected pulse from a beam splitter. The rise time is most likely due to carrier cooling (Ref. 8). (c) Switching times of the three different types of PhC and the unpatterned ridge waveguide reference sample. The switching time is characterized by the $1/e$ time of the nonlinear transmission, as determined by an exponential fit to the data in (a) and (b). (d) Power dependence of the transmission change for the W1 and ridge waveguides.

waveguides were added to separate the MZI arms by 25 μm. PhC sections were incorporated into the MZI arms as shown in Fig. 1(a). The air holes act as surface recombination centers and hence the lifetime of the excited carriers is reduced. In previous studies, we demonstrated that lifetimes below 10 ps could be achieved in this way,[6–8] and that the surface recombination rate can be controlled by the design of the PhC.[15]

Three different types of PhC waveguides were investigated and compared to a reference sample consisting of an unpatterned ridge waveguide of width 1.5 μm. The first two PhC types were line defect waveguides in which one or three rows of holes were removed in order to create “W1” and “W3” [see Fig. 1(b)] waveguides, respectively. The third type consisted of a uniform square lattice of holes and employed the self-collimation phenomenon.[16] The PhC waveguides were designed from the band structure calculated by the plane wave expansion method. The period a and hole radius r were, respectively, 280 nm and $0.25a$ for the W1 waveguide, and 330 nm and $0.32a$ for the W3. The self-collimator was fabricated with a period $a=260$ nm and hole radius $r=0.25a$, and the self-collimation occurs at frequency $\nu=0.286c/a$ in the second band for light propagating in $\Gamma-X$ direction.

The nonlinear switching dynamics were measured by pump-probe techniques using a femtosecond Ti:sapphire regenerative amplifier and an optical parametric amplifier (OPA) as shown in Fig. 2. The pulse duration was 130 fs and the repetition rate was 1 kHz. 800 nm pulses from the Ti:sapphire amplifier were used for the pump together with 920 nm pulses from the OPA for the probe. The pump beam was focused to a diameter of 8 μm on one arm of the MZI with a typical fluence of 3.4 mJ/cm^2, giving a switching energy of 1.7 nJ. The weaker probe beam was end-fire coupled to the waveguide, and the transmitted probe power was measured with a Si detector. The pump-induced transmission change was then detected by chopping the pump beam and using lock-in techniques.

The pump-probe results for the three different types of PhC design are shown in Fig. 3(b), together with the results for the ridge waveguide reference sample in Fig. 3(a). Following the rapid change in transmission near zero time delay, the signal recovers on a variety of timescales determined by the carrier lifetime. The carrier lifetime of the ridge waveguide reference sample deduced from Fig. 3(a) is 61 ps. This is about a factor of two faster than comparable bulk AlGaAs material[17] and indicates that surface recombination is important even without a PhC. This is not unreasonable, given that the ridge width was only 1.5 μm.

The introduction of a PhC changes the average distance of the carriers from the surface, thereby increasing the effect of surface recombination.[15] The W3 and W1 waveguides are approximately 1.2 μm and 470 nm wide, respectively, which leads to a corresponding reduction in the carrier lifetime. The self-collimator device does not require a defect in the lattice, and thus had an even larger fraction of etched holes, which further enhances the surface recombination rate. The veins of semiconductor material left between the PhC hole pattern are of order 140-nm-thick, which is less than half of the value for the W1. Correspondingly, we measure a reduction in the carrier lifetime by more than a factor of 2, down to 3 ps. Figure 3(c) compares the switching times (defined as the $1/e$ time of the nonlinear transmission) of the three different types of PhC design to the reference sample. There is a clear difference between the PhC samples that scales with the distance the carriers have to diffuse to reach the surface, with the self-collimator giving the fastest response.

Figure 3(d) shows the dependence of the nonlinear transmission on the pump power. A clear saturation of the switching contrast was observed above 2.25 μW average power (4.5 mJ/cm^2 laser fluence). This saturation is possibly caused by thermal effects creating a steady-state imbalance between the arms.

Since the pump photon energy is below the AlGaAs band gap, the optical nonlinearity arises from the free carriers generated by two-photon absorption (TPA). Using a simple free carrier model for TPA nonlinearities[7] and a value of 3.1×10^{-8} cm/W for the TPA coefficient,[18] the refractive index change in the AlGaAs core is $\Delta n\sim0.01$ for the estimated carrier density of 2×10^{18} cm^{-3} at a fluence of 3.4 mJ/cm^2. Given that the PhC devices, by their very nature, have a smaller material fill factor than the ridge waveguides, the TPA rate is lower for a given pump power, with a correspondingly reduced effective refractive index change. This is apparent from the difference in the switching contrast between the “bulk” and the PhC waveguides in Figs.

3(a) and 3(b). For example, finite-difference time-domain (FDTD) simulations indicate that the absorbed pump power in the self-collimator waveguide is about two times smaller than in the ridge waveguide.

At the operating wavelength of our experiments, the nonlinear absorption and phase modulation contributed approximately equally to the modulation depth. With an effective Δn of 0.005 (i.e., 0.01/2, where the factor of two accounts for the reduced fill factor) and an interaction length l of 8 μm, we obtain $\cos\Delta\phi=0.96$ at a wavelength of 0.92 μm. The free carrier absorption is of order 50 cm^{-1} at our carrier density,[19] which corresponds to an attenuation of 4% and a value for the normalized amplitude term of $\sqrt{I_1 I_2}=0.98$. We thus expect a modulation depth of 4% from Eq. (1), which corresponds closely to the measured value for the self-collimator device shown in Fig. 3. This relatively low contrast could be significantly enhanced by using slow light effects. For example, a switching contrast exceeding 10 dB should be possible with the same parameters for a tenfold reduced group index, which can realistically be achieved.[11,20]

In conclusion, we have demonstrated ultrafast switching in a III-V PhC MZI device. All of the PhC devices are faster than the reference, with the shortest switching time of 3 ps being obtained for the self-collimator device. These results highlight the exciting potential of III-V PhCs in all-optical switching applications.

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