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A. Villeneuve
University of Central Florida

C. C. Yang
University of Central Florida

P. G. J. Wigley
University of Central Florida

G. I. Stegeman
University of Central Florida

J. S. Aitchison

See next page for additional authors

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Authors

A. Villeneuve, C. C. Yang, P. G. J. Wigley, G. I. Stegeman, J. S. Aitchison, and C. N. Ironside

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K. Al-hemyari, A. Villeneuve, J. U. Kang, J. S. Aitchison, C. N. Ironside, and G. I. Stegeman

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Ultrafast all-optical switching in GaAlAs directional couplers at 1.55 μm without multiphoton absorption

K. Al-hemyari
Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow G12 8QQ, Scotland

A. Villeneuve and J. U. Kang
CREOL, University of Central Florida, 12424 Research Parkway, Orlando, Florida 32826

J. S. Aitchison and C. N. Ironside
Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow G12 8QQ, Scotland

G. I. Stegeman
CREOL, University of Central Florida, 12424 Research Parkway, Orlando, Florida 32826

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We demonstrate ultrafast, high throughput, all-optical switching in optimized, 2-cm-long, half- and full-beat-length nonlinear directional couplers operated at 1.55 μm, below half the band gap of $Ga_{0.82}Al_{0.18}As$. The long device length allowed the elimination of nonlinear loss and resulted in a switching peak power and energy of 85 W and 65 pJ, respectively.

Recent theoretical and experimental investigations into the origin of the nonresonant nonlinearity, n_2, have shown that the magnitude of the effect has resonance close to the two-photon absorption (TPA) edge.[1] Earlier experimental investigations into semiconductor waveguides have shown that TPA imposes severe limitations on the practical operation of all-optical switching devices.[2] Therefore, to avoid TPA at optical communication wavelengths in the $\lambda = 1.55$ μm band, semiconductors are selected with a half-band-gap energy slightly above the optical communication spectral region. For the GaAlAs semiconductor system this corresponds to $Ga_{0.82}Al_{0.18}As$. We have already demonstrated ultrafast all-optical switching in a number of different waveguide geometries at photon energies below half the band gap of $Ga_{0.82}Al_{0.18}As$.[3–5] However, although TPA was no longer a problem, the switching performance in the nonlinear directional couplers (NLDCs) was hampered by three-photon absorption (3PA).[4] In principle, this nonlinear absorption can be avoided by reducing the switching power, i.e., by employing a longer interaction length to obtain the required phase change for the directional coupler to switch. In this letter we show that this approach does work. Specifically we present results on ultrafast all-optical switching of NLDCs without significant multiphoton absorption at $\lambda = 1.55$ μm. We also report the first observation of switching in an integrated optics, full-beat-length coupler. We believe that with the possible exception of marginal improvements in the linear loss, the NLDCs presented here approach the best that can be achieved in this material system.

The material structure of the wafer used to fabricate the NLDC is described in Ref. 3. The AlGaAs epitaxial layers were grown by molecular beam epitaxy, and consisted of a 1.5-μm-thick $Ga_{0.82}Al_{0.18}As$ guiding region, a 1.5-μm-thick $Ga_{0.75}Al_{0.25}As$ upper cladding layer, and a 4-μm-thick $Ga_{0.75}Al_{0.25}As$ lower cladding layer. The epitaxial layers were grown on a semi-insulating GaAs substrate. Standard optical lithography and reactive ion etching (using $SiCl_4$ gas) were used to fabricate directional couplers with a range of different rib widths and spacings, etched to a depth of 1.45 μm. The input guide of the NLDC extended to the input edge of the chip, while the coupled guide is offset by a short distance from the input edge to ensure that the input beam is coupled only into the input guide. The NLDC has a coupling region 2.14 cm long and the total length of the chip is 2.2 cm.

A single beam experiment was used to examine the NLDC as an all-optical switch by monitoring the output transmission of the NLDC as a function of the input intensity. A NaCl:OH^- color center laser was operated at 1.55 μm with 76 MHz repetition rate, either in the synchronously pumped mode with 4–6 ps pulses, or in the coupled cavity mode with 400–500 fs pulses. Up to 100 mW average power was coupled into and out of the waveguides using ×20 and ×60 microscope objectives, respectively. The polarization of the incident beam was set to TE or TM polarization using a halfwave plate. Near-field mode profiles of the waveguides using a Hamamatsu camera were used to verify that waveguides with rib widths of up to 6 μm to support a single mode. The first NLDC studied consisted of 5 μm channels separated by 7 μm. The effective cross-sectional area of the waveguide was 12 μm^2. The NLDC is one coupling length L_c for the TE polarization and 1.4 L_c for the TM polarization, where L_c is the shortest length required for complete transfer from the incidence ("bar") to the "cross" channel.

Figure 1(a) shows a plot of the pulse energy transmission of the NLDC (cross, bar, and total) as a function of the peak input intensity for 3.8 ± 0.2 ps pulses and TE polarization. The measured input power did not include the coupling loss to the waveguide and the waveguide facets reflectivity. At low input peak intensity the NLDC is at

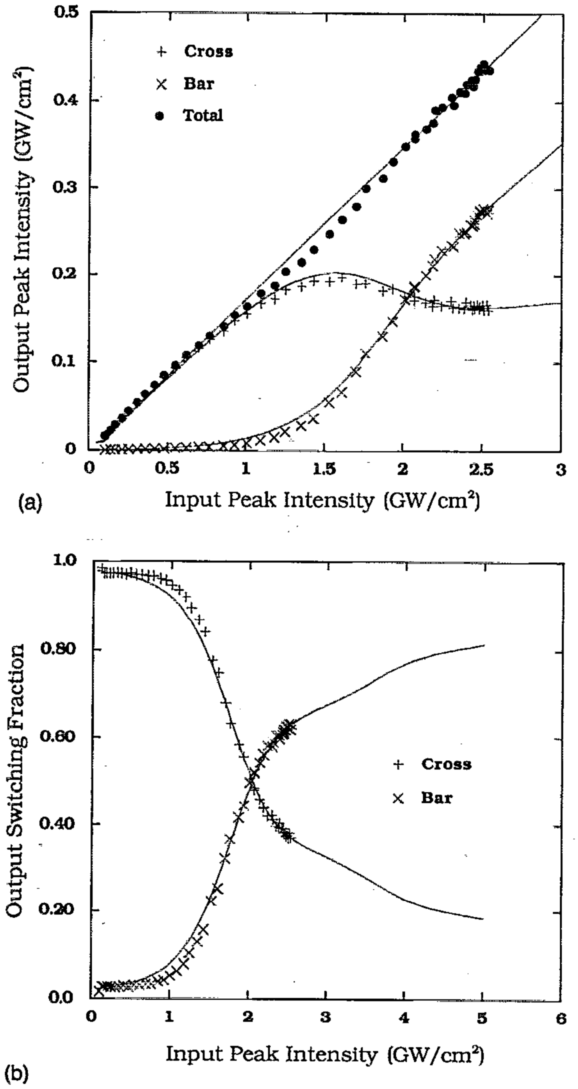

FIG. 1. (a) The transmission of the pulse energy in cross, bar, and total states of a half-beat-length NLDC as a function of the input peak intensity measured with 3.8 ps pulses. The symbols are the experimental results and the solid curves are the theoretical simulation. (b) The normalized switching characteristic of the NLDC.

the cross state (i.e., the output emerged from the coupled guide). As the input peak intensity is increased most of the light stays in the input guide (i.e., bar state). Complete switching from the cross to the bar state is not possible with pulsed inputs due to pulse breakup which occurs when the response time of the nonlinearity is shorter than the pulse duration.[6] The linear behavior of the total output transmission indicates that there is no multiphoton absorption, even at high powers. The solid lines are the numerical simulation, using $n_2 = 1.2 \times 10^{-13}$ cm²/W and no TPA and 3PA absorption. This simulation agrees well with the experimental results. Figure 1(b) shows a plot of the normalized output transmission of the cross and bar states of the NLDC as a function of the peak input intensity. The data which are derived from Fig. 1(a) clearly illustrate the switching effect. Assuming 30% facet reflectivity and 60% coupling efficiency into the waveguide, the peak pulse switching power is 85 W.

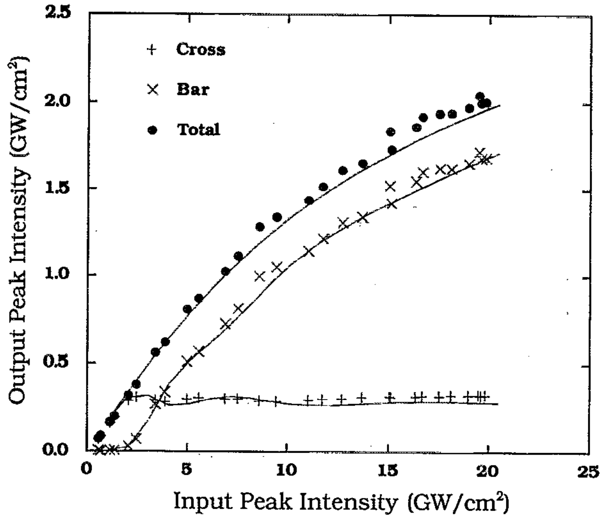

FIG. 2. The transmission of the pulse energy in cross, bar, and total states of a half-beat-length NLDC as a function of the input peak intensity measured with 400 fs pulses. The symbols are the experimental results and the solid curves are the theoretical simulation.

The same measurements were repeated with $\approx$400 fs and are shown in Fig. 2. The interesting feature in this figure is that the total output transmission is linear for input peak intensities up to 10 GW/cm² (before the sample), equivalent to $\approx 6\pi$ phase change. At higher input powers, the total output transmission is no longer linear with input power, primarily due to 3PA. Neglecting TPA, including group velocity dispersion (GVD), and assuming the linear and 3PA coefficients to be $\alpha = 0.15$ cm^{-1} and $\beta_3 = 0.055 \times 10^{-18}$ cm^3/W^2, respectively, the theoretical simulation fits the experimental data. Using this value of β_3 and the critical intensity of 0.7 GW/cm², we found a value for the three-photon figure of merit $V = I_c \lambda \beta_3 / n_2$ of 0.05.[7] V should be less than 1 for switching to occur, which is certainly satisfied in this case.

A pump-probe experiment was used to examine the pulse broadening and recovery time of the NLDC. A TE polarized pump beam and TM polarized probe beam were coupled into the input guide of the NLDC, and a polarizer was used at the output to block the pump beam. The time resolved switching characteristics of the NLDC (i.e., switching fraction as a function of delay time between the pump and probe pulses) were measured with pulse widths of 6.6 and 430 fs. For the broad pulse, the NLDC output pulses followed the temporal shape of the input pulse, even at the maximum input peak power where a large spectral broadening via self-phase modulation occurred. However, for the short pulse, the FWHM of the cross and bar states, shown in Fig. 3, was $\approx$860 fs, i.e., the input pulse experienced a temporal broadening by a factor of $\approx$2. This broadening is due to group velocity dispersion which cannot be ignored for subpicosecond, high input peak intensities because the spectral broadening due to the SPM effect is large.

The switching characteristics of a one-beat-length ($2L_c$) NLDC fabricated on the same AlGaAs chip were investigated.[8] The device consisted of 6-μm-wide rib channels, separated by 5 μm. Figure 4 shows the normalized

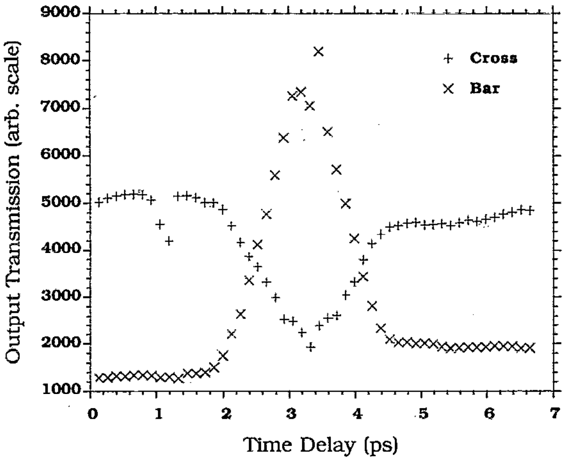

FIG. 3. The output transmission of the bar and cross states for probe pulses transmitted through a half-beat-length NLDC, as a function of the delay time between the 430 fs pump and probe pulses. The pump beam was TE polarized and orthogonal to the TM probe beam.

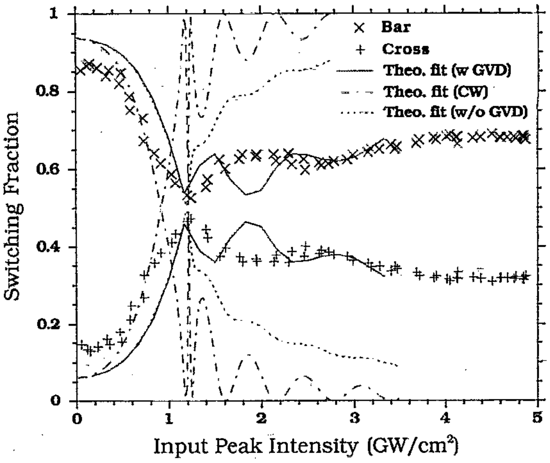

FIG. 4. The switching fraction in the cross and bar states of the full-beat-length NLDC as a function of the input peak intensity for 400 fs TE polarized pulses. The solid and dashed curves are simulations with and without group velocity dispersion, respectively. The dash-dotted line is the cw response of the device.

output transmission of the cross and bar states as a function of the peak intensity (GW/cm^2). Also shown by the dash-dotted line is the theoretical cw response. Clearly the use of pulses dramatically "smears out" the cw response, with the minima and maxima achieving only 50% switching. The dashed line is the best fit to the data at low intensities (including the measured 3PA) from which it is clear that another effect plays a significant effect at high intensities. By also including group velocity dispersion (GVD $=8.7\times10^{-25}$ s^2/m)[9] in the modeling, we were able to obtain a good fit to the data, see Fig. 4. (We found that GVD had a negligible effect on the half-beat-length coupler: the details of the effect of GVD on NLDCs will be reported elsewhere.)

In summary, we have presented results on ultrafast, high throughput all-optical switching in optimized $\mathrm{Ga_{0.82}Al_{0.18}As}$ NLDCs, operated without nonlinear absorption below half the band gap at 1.55 μm. The peak switching power of the one half-beat-length NLDC is $\approx$85 W ($\approx$65 pJ switching energy). Although GVD has little effect on NLDC operation with 6.6 ps pulses, the output pulses were broadened and the response changed with 430 fs pulses. We also reported for the first time experimental and theoretical results on switching in a full-beat-length integrated NLDC.

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Note added in proof: We note that another approach to all-optical switching using active semiconductors has been recently reported with even lower switching energies, 10 pJ.[10]

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