

All-Optical Switching with Low-Peak Power in Microfabricated AlGaAs Waveguides

R. P. Espindola, *Member, IEEE*, M. K. Udo, D. Y. Chu, *Member, IEEE*, S. L. Wu, S. T. Ho, *Member, IEEE*, R. C. Tiberio, P. F. Chapman, and D. Cohen

Abstract—We report all-optical switching with low-peak power in a microfabricated AlGaAs waveguide operating at 1.6 μm . We show that by using a 1-cm long microfabricated strongly-guided waveguide with 0.8 μm by 0.9 μm mode cross-sectional area, switching is achieved with an average power of 1.2 mW for 82-MHz mode-locked 430 fs pulses. The estimated peak pump power and pulse energy inside the microfabricated waveguide were ~ 30 W and ~ 14.6 pJ, respectively, which is 5–10 times lower than the values needed with conventional waveguides. In terms of a practicality index defined via switching power times waveguide length, this waveguide has around the best value.

I. INTRODUCTION

IN an ultra-high speed network, be it local network or long haul fiber network, ultrafast all-optical switches are needed to accomplish the network connection and switching. All-optical switching has been demonstrated in various configurations such as the nonlinear directional coupler [1] and the asymmetric Mach–Zehnder interferometer [2]. However, in order for an optical switch to be practical, it is necessary for the device to be operated at low-peak power and be compact in size, which requires nonlinear materials with high nonlinearity and low loss. A measure of a material's usefulness for optical switching applications is given by a figure of merit [1], [3] defined as $F = n^{(2)}/(\alpha\lambda)$, where $n^{(2)}$ is the second-order nonlinear refractive index, α is the total (linear and nonlinear) absorption coefficient, I is the laser intensity needed to achieve optical switching (determined by $n^{(2)}$ and the medium's length), and λ is the free space optical wavelength. In order for a material to be usable for all-optical switching, it is necessary that $F \geq 1$. In particular, F is fundamentally limited by the two-photon absorption component in α given by $\alpha^{(2)}I$, resulting in an intensity independent contribution to F , i.e., its effect cannot be reduced

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R. P. Espindola, M. K. Udo, D. Y. Chu, S. L. Wu, and S. T. Ho are with the Department of Electrical Engineering and Computer Science, The Robert R. McCormick School of Engineering and Applied Science, Northwestern University, Evanston, IL 60208 USA.

R. Tiberio is with the National Nanofabrication Facility, Knight Laboratory, Cornell University, Ithaca, NY 14853 USA.

P. F. Chapman was with the National Nanofabrication Facility, Knight Laboratory, Cornell University, Ithaca, NY 14853 USA. He is now with Symbios Logic, Inc., Fort Collins, CO 80521 USA.

D. Cohen is with the School of Electrical Engineering, Cornell University, Ithaca, NY 14853 USA.

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by varying the length of the medium. Recently, Ho *et al.*, [1], [4] demonstrated that in AlGaAs the two-photon absorption is drastically reduced in the region below half the energy gap ($\sim 1.6 \mu\text{m}$), enabling the material to meet the figure of merit requirement described above. Another important parameter to consider is the power required to operate the device. For the Mach–Zehnder configuration described in this work, the power required is the power needed to provide a π phase shift within the length of the nonlinear medium. For practical applications, it is reasonable to aim for optical peak power in the order of watts, which is the peak power that can be achieved with currently available pulsed semiconductor lasers. In addition, the compactness of a device is another important practical factor and devices with dimensions of the order of centimeters are desirable.

In this letter, we show that by using a 1 cm long microfabricated strongly-guided waveguide with 0.8 μm by 0.9 μm fundamental mode cross-sectional area, ultrafast all-optical switching can be achieved at a peak power of 30 W, which is not too far from the power requirement for practical applications. We also show that for a conventional 9-mm long rib waveguide with 4.5 μm by 2.7 μm mode cross-sectional area, switching is achieved at a much higher peak power of 550 W. We first describe the material composition of the waveguides and the fabrication procedure for both the conventional and the microfabricated rib waveguides. We then describe the experimental setup and finally present our experimental results and conclusions.

The AlGaAs epitaxial layers were grown by MBE and consisted of a $\text{Al}_{0.23}\text{Ga}_{0.77}\text{As}$ guiding region on top of a $\text{Al}_{0.60}\text{Ga}_{0.40}\text{As}$ lower cladding layer grown on a semi-insulating GaAs substrate. The conventional rib waveguide had a 5- μm thick guiding region, a 2- μm thick cladding layer, a rib height of 2 μm and rib width of 4 μm . The microfabricated waveguide had a 1.5- μm thick guiding layer, a 2.5- μm thick lower cladding layer, and its height and width were both around 1.5 μm . The 9-mm long rib waveguide was fabricated using a conventional photolithography procedure and a chemical etching using $\text{H}_3\text{PO}_4 : \text{H}_2\text{O}_2 : \text{H}_2\text{O}$ (1 : 1 : 35 volume ratios) as etchant. The 1 cm long microfabricated waveguide was patterned via conventional photolithography, but etched via chemically assisted ion beam etching (CAIBE) with chlorine gas in conjunction with an argon-ion beam. Fig. 1 shows a SEM picture of the 1-cm long microfabricated strongly-guided waveguide with 1.5 μm by 1.5 μm physical cross-sectional area and 0.8 μm by 0.9 μm mode cross-

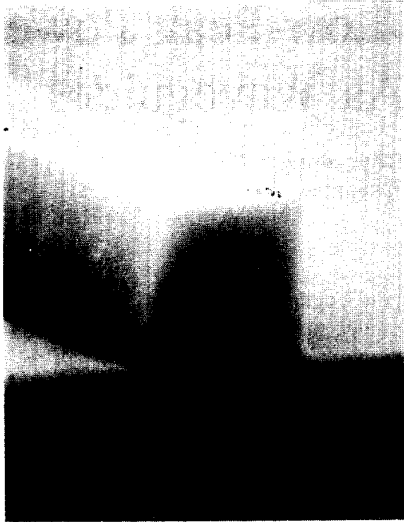


Fig. 1. SEM picture of the microfabricated strongly-guided AlGaAs waveguide.

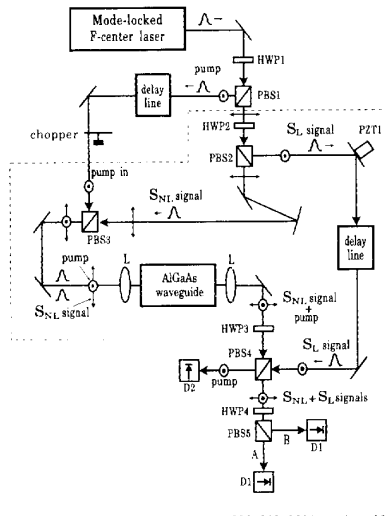


Fig. 2. Experimental set up of the Mach-Zehnder configuration for all-optical switching using AlGaAs waveguides.

sectional area. This fabrication procedure gives smooth waveguide side walls, which is essential for minimizing waveguide propagation losses.

Fig. 2 shows the experimental setup for the all-optical switching using AlGaAs waveguides in the Mach-Zehnder configuration, where the portion comprising the Mach-Zehnder interferometer is indicated by the dotted lines. This setup is similar to the pump-probe $n^{(2)}$ measurement scheme reported by us in a separate paper [5]. The details of the all-optical switching experiment are as follows.

An additive pulse mode-locked (APM) color center laser (NaCl:OH) is used to generate high peak intensity pulses with pulse width of 430 fs and a pulse repetition rate of

82 MHz at $\lambda = 1.6 \mu\text{m}$. As shown in Fig. 2, the output of the color center laser is split at the polarization beam splitter PBS1 into a strong pump beam and a weak signal beam with intensity ratio 9 to 1, which can be adjusted by the half-wave plate HWP1. The weak-signal beam is further split at PBS2 into S_{NL} and S_L beams that propagate through the nonlinear and linear arms of the Mach-Zehnder interferometer, respectively. Here, we refer to the arm containing the AlGaAs waveguide as the nonlinear arm of the interferometer. The orthogonally polarized pump and S_{NL} signal beams are then combined at the polarization beam splitter PBS3 (i.e., spatially overlapped but still orthogonally polarized) and coupled into the waveguide. The optical coupling into and out of the waveguide was done by the end-firing coupling method using $40\times$ microscope objective lenses with a numerical aperture of 0.6. To minimize losses, both the front and back facets of the waveguide were antireflection coated. After going through the waveguide, the pump beam is separated from the signal beam by the polarization beam splitter PBS4. The pump beam is then detected at detector D2, whose output gives the pump beam intensity after the waveguide. The S_L signal, generated at PBS2, is recombined at the polarization beam splitter PBS2 with the orthogonally polarized S_{NL} signal from the waveguide. The polarizations of S_L and S_{NL} beams after PBS4 are rotated by 45 degrees with a half wave plate (HWP4) and the resulting beam passes through another polarization beam splitter PBS5, where the interference between the S_L and S_{NL} signal beams occurs (the combination of PBS4, HWP4, and PBS5 is equivalent to a polarization insensitive 50/50 beam splitter). The resulting interference signal beam exits at either port A or B of PBS5, depending on whether there is constructive or destructive interference [5]. To demonstrate all-optical switching, the phase of the S_L signal pulse is adjusted by a piezoelectric transducer (PZT1) and its intensity adjusted by the combination of HWP2 and PBS2 so that in the absence of the strong pump beam, the combined signal pulses exit from port A of PBS5. When the strong pump pulse overlaps the signal pulse inside the waveguide causing a π phase shift of the S_{NL} signal pulse via cross-phase modulation, the output signal pulses at PBS5 are switched from port A to port B.

Fig. 3 demonstrates ultrafast all-optical switching using the microfabricated AlGaAs waveguide. The interferometer was set so that the output signal at port A has maximum intensity. The solid curve represents the signal at port A of the switch, while the dotted curve shows the pump on and off. When the pump is on the output signal decreases showing the signal being switched from the output port A to B. From the figure we see that there is about 60% switching, limited by the nonlinear cross-phase modulation due to the nonsquare intensity profile of the pump pulses and by the mode matching efficiency between the interfering signals at PBS5. When the pump and S_{NL} signal pulses in the waveguide are delayed from each other by one or more pulse widths, the amount of switching reduces to zero, demonstrating that the switching speed is faster than 430 fs. From our experimental measurement, we conclude that the π nonlinear phase shift needed for optical switching was achieved with a 1.2-mW average power in the waveguide for 82 MHz mode-locked 430-fs pulses at

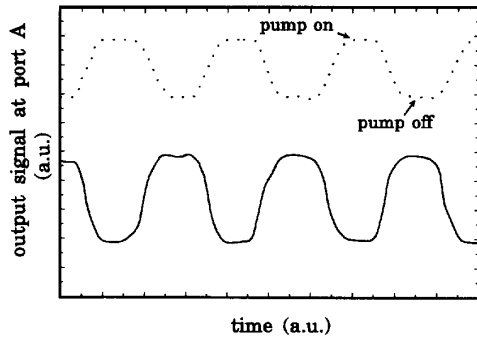


Fig. 3. The bottom trace (solid curve) shows the modulated output signal at port A of the switch as function of time, while the top trace (dotted curve) shows the pump on and off. When the pump is on the output signal increases showing the signal being switched from output port A to B.

1.6 μm wavelength. The estimated peak pump power and pulse energy inside the microfabricated waveguide were ~ 30 W and ~ 14.6 pJ, respectively. Currently, the net coupling efficiency in and out of the microfabricated waveguide is about 10%, which could be improved in the future by tapered waveguides or coupling lenses with larger numerical aperture. The propagation loss in the 1 cm long waveguide is estimated to be less than 10 % using the cut-back method. For the 9-mm long conventional rib waveguide, switching was achieved with 22-mW average power and the estimated peak power and pulse energy inside the waveguide were ~ 550 W and ~ 270 pJ, respectively. Note that the peak pump power necessary for π nonlinear phase shift can be smaller by a factor of $\frac{2}{3}$ if the pump and probe beams have the same polarization. This is because cross-phase modulation (XPM) is $\frac{2}{3}$ as strong as self-phase modulation (SPM) for an isotropic material like AlGaAs [4]. Hence, for the case where the pump and probe beams have the same polarization, the switching peak pump power and pulse energy for the microfabricated waveguide can be reduced to 20 W and 10 pJ, respectively.

Since the switching pump power p is inversely proportional to the length of the waveguide ℓ , the product $p * \ell$ for a given nonlinear waveguide medium is a constant and can be used as a practicality index for the realization of compact ultrafast all-optical switching devices. Based on the discussion in the introductory paragraph, we propose that practical devices should have $p * \ell$ around unity or smaller, where p is in

watts and ℓ in centimeters. Our microfabricated waveguide, for the case where the pump and probe beams have the same polarization, has $p * \ell = 20$ W-cm that is lower than the value recently reported for an optical nonlinear directional coupler [6] with $p * \ell = 130$ W-cm (this directional coupler has material composition similar to our waveguide, but larger waveguide mode structure). For comparison purposes, it is useful to note that the $p * \ell$ value for the usual single-mode silica fiber is around 300000 W-cm. However, optical fibers have the advantage that their lengths can be very long without incurring much loss, while waveguides cannot.

In conclusion, we used a 1 cm long AlGaAs microfabricated strongly-guided waveguide to demonstrate a compact ultrafast all-optical switch with low switching power and low practicality index of $p * \ell = 30$ W-cm (with pump and probe orthogonally polarized). By increasing the length of the microfabricated waveguide, it may be possible to achieve a low switching peak power of around 10 W.

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