Ultrafast all-optical multiple quantum well integrated optic switch

C. Kim, D.A. May-Arrioja, P. LiKamWa, P. Newman and J. Pamulapati

An all-optical integrated Mach-Zehnder interferometer switch is implemented using selective area disordering of a multiple quantum well structure. Ultrafast all-optical switching with an adjustable switching window ranging from 2 to 100ps is demonstrated. The switch contrast ratio in this preliminary device is measured to be 9dB.

Introduction: Ultrafast all-optical switches are essential components that will be required to implement future ultrafast optical time division multiplexing (OTDM) networks that have the potential of providing truly flexible bandwidth on demand at burst rates of 100Gbit/s [1] and beyond. Monolithic photonic integration would provide considerable advantages, such as improved mechanical stability and reliability, general reduction in size and resultant increases in component density and reductions in cost, simplified packaging and potential improvements in data handling rates. All-optical switches made of III-V semiconductor quantum well structures have many advantages because of the large carrier induced nonlinearities of the material [2] and the potential for monolithic integration of various optical components by post-growth modification of the absorption spectrum of selected regions. Selective area quantum well intermixing techniques [3, 4] enable the control of the effective bandgap energy of the quantum well structure spatially across a wafer and provide a simple, reliable and low-cost integration approach compared to other schemes, such as selective area epitaxy or selective etching and regrowth.

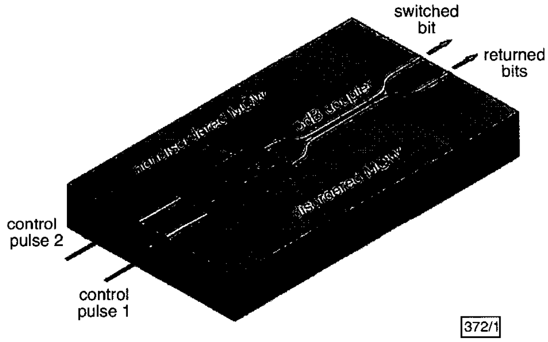

Fig. 1 *Integrated all-optical interferometric switch*

In this Letter we present a symmetric Mach-Zehnder all-optical switching device (Fig. 1) that is fabricated on a GaAs/AlGaAs multiple quantum well structure using a quantum well intermixing technique. Although the switching is based on carrier-induced nonlinearities of the multiple quantum well structure, the device geometry allows switching using two control pulses separated by a small time delay to achieve ultrafast switching that is not restricted by the slow relaxation time of the nonlinearities [5].

Integrated all-optical switch: The all-optical Mach-Zehnder interferometric (MZI) switching device with a 3dB coupler consists of single-mode ridge waveguides fabricated on a GaAs/AlGaAs multiple quantum well structure. SiO_2-capped impurity-free vacancy disordering (IFVD) of the multiple quantum wells is used to blue-shift the bandgap of the whole sample except for the sections containing the nonlinear arms of the interferometer. The slab waveguide structure grown by molecular beam epitaxy contains a multiple quantum well (MQW) core bounded on the top by a 0.5μm thick $Al_{0.3}Ga_{0.7}As$ cladding layer and on the bottom by a 2.5μm thick $Al_{0.3}Ga_{0.7}As$ lower cladding layer. The MQW core is made up of 38 alternating GaAs quantum well $Al_{0.3}Ga_{0.7}As$ barriers each 7nm thick. The whole structure is capped by a 50nm thick GaAs layer.

The integrated symmetric Mach-Zehnder interferometer with two signal inputs and a 3dB directional coupler recombiner was fabricated using contact mask photolithography and wet chemical etching. The sample was then coated with a 200nm thick film of SiO_x by plasma enhanced chemical vapour deposition. The 100 × 500μm nonlinear sections were defined on the top of the MZI separate arms by opening windows in the SiO_x film using photolithography and reactive ion etching. The sample was then annealed for 20s at 980°C using a rapid thermal annealing process to intermix the quantum wells in the regions covered by the SiO_x film. The room temperature photoluminescence spectra of the sample showed that the bandgap energy of the MQW layer in the silica capped sections of the sample was blue shifted by 64nm, while the uncapped regions of the sample only experienced a blue shift of 6nm.

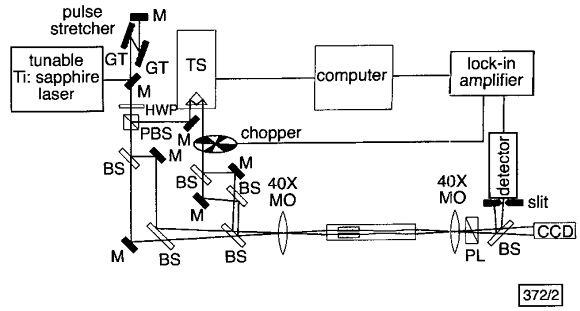

Fig. 2 *Experimental setup for pump-probe measurement*

M: mirror, GT: grating, BS: beam splitter, HWP: half-wave plate, PBS: polarising beam splitter, MO: microscope objective, PL: polariser, TS: translation stage

Switching measurements: The device, cleaved to an overall length of 4mm, was tested using a pump-probe arrangement shown schematically in Fig. 2. A Kerr-lens mode-locked Ti:sapphire laser operating at 845nm was used as the source of the optical signal and control pulses. Pulses from the laser were stretched to 1ps using a twin grating pulse stretcher. The laser output beam was split into two signal beams and two control beams. The signal beams were mechanically chopped and each beam was launched separately into the two arms of the device. The control beams were also launched separately into the two arms of the device. The optical beams were end-fire coupled into the device using a single 40× microscope objective lens, and the output beams were collected by a 40× microscope objective lens and monitored simultaneously on a CCD camera and a photodetector. The photodetector was connected to a lock-in amplifier for the time delayed pump-probe measurements.

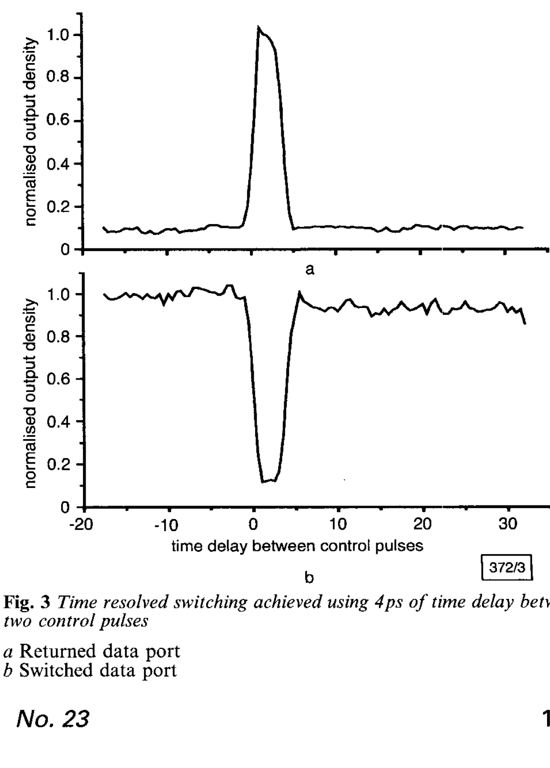

Fig. 3 *Time resolved switching achieved using 4ps of time delay between two control pulses*

a Returned data port
b Switched data port

The temporal variations of the output signal intensities from the two ports of the device, in response to two control pulses separated by a preset delay of 4ps, are shown in Fig. 3. It can be clearly observed from the plots of Fig. 3 that the rise time and fall time of the device switching response are both of the order of 1ps, which corresponds very closely to the pulse width of the switching pulses. The temporal width of the gating window should be fully adjustable depending on the width of control pulses and the carrier lifetime in the sample. The particular device in this experiment had a carrier lifetime of the order of several nanoseconds and therefore no noticeable recovery is observed for several tens of picoseconds in the switching response when only one switching pulse is employed. Using control pulses of 1ps duration, the temporal gating window of the device was continuously adjusted from 2ps to several tens of picoseconds.

Summary: We have demonstrated an all-optical integrated Mach-Zehnder switch realised by means of selective area SiO_x-capped impurity-free vacancy disordering (IFVD) of the underlying multiple quantum well core structure. Ultrafast all-optical switching with as short as 2ps gating window has been achieved with a switch contrast ratio of 9dB. The gate timing window is continuously adjustable and the rise and fall times of 1ps obtained in this experiment closely follow the duration of the control pulse.

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C. Kim, D.A. May-Arrioja and P. LiKamWa (*School of Optics/CREOL, University of Central Florida, Orlando, FL 32816, USA*)

P. Newman and J. Pamulapati (*Army Research Laboratory, AMSRL-EP-EE, Adelphi, Maryland 20783, USA*)

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Passive harmonic modelocking in monolithic compound-cavity laser diodes

D.A. Yanson, M.W. Street, E.A. Avrutin, S.D. McDougall, I.G. Thayne and J.H. Marsh

Passive harmonic modelocking operation of novel compound-cavity laser diodes is demonstrated. The modelocking rates can be readily scaled up into the terahertz domain and enable applications in terahertz imaging, medicine, ultrafast optical links, and atmospheric sensing.

Introduction: Passive harmonic modelocked laser diodes are capable of generating pulses at repetition rates in excess of 1.5THz [1]. Such ultrafast lasers may find applications as local oscillator sources for millimetre-wave imaging, radio astronomy and atmospheric sensing, and also, at lower frequencies, serve as clock sequence generators in optical communication links. A harmonic modelocked laser produces an optical pulse train at a harmonic of the fundamental round-trip frequency, which can be achieved with either of the two main techniques: colliding pulse modelocking (CPM) and compound cavity modelocking (CCM). The (asymmetric) CPM effect has been used to obtain modelocking at repetition frequencies up to 860GHz [2]. Rates of up to 1.5THz have been achieved with the use (albeit unintentional) of the CCM effect [1]. However, no attempts have been made thus far to implement reproducible CCM operation in high-speed lasers. Here, we report reproducible third harmonic modelocking operation at 131GHz from what is, to our knowledge, the first purpose-fabricated monolithic CCM laser diodes at $\lambda = 0.86\mu m$, based on a construction proposed theoretically in [3, 4].

In [3, 4], a theory of CCM was developed predicting modelocking at the Mth harmonic for a compound cavity device with a section ratio $L_1/L_2 = 1/m$, with $M = (m + 1)$ and a repetition rate $f = Mf_F$, where f_F is the fundamental modelocking frequency. Such a cavity provides specific spectral selectivity resulting in the M-fold multiplication of the mode separation in the lasing spectrum, $\Delta\Lambda_{CCM} = M\Delta\lambda_{F\text{-}P}$, ($\Delta\lambda_{F\text{-}P}$ is the cavity's Fabry-Perot mode spacing). Simulations also suggest that Mth harmonic CCM can only take place when all but every Mth mode are suppressed.

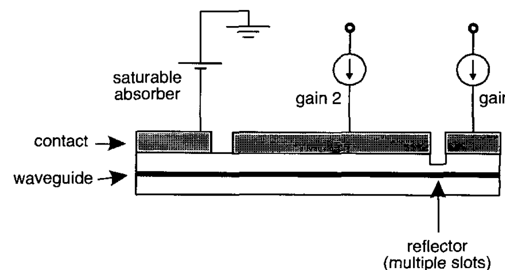

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Fig. 1 *Schematic diagram of monolithic compound-cavity device with etched slot reflector*

Fabrication: The experiments here were performed with three-section GaAs/AlGaAs double quantum-well ridge-waveguide laser diodes, incorporating a saturable absorber and two gain sections, with an etched reflector between them (see Fig. 1). The reflector was defined by e-beam lithography and dry-etching and consisted of several (one to four) sub-wavelength slots (~200nm each) cutting deep into the waveguide core at a specific position within the cavity.

Accurate compound cavity ratios are essential if harmonic effects are to occur in CCM lasers. However, the accuracy of a conventional wafer scriber used to cleave the devices to required lengths proved insufficient, and a special wet-etch facilitated cleaving process was developed. This involved the use of a fast anisotropic etch to produce deep cleavage nicks from lithographically-defined seed windows. The resulting length error was of the order of +/–3μm.

Results: The threshold current of etched slot devices typically increased by 30 to 70% compared to unperturbed lasers with identical lengths and depended strongly on the number and size of the slots. The optical power was up to 2.5mW per facet in continuous wave operation. The devices manifested the expected increase in spectral mode separation, while the number of modes in the spectrum varied with the bias applied to different contact sections. Fig. 2*a* shows a typical spectrum from a 1/2 ratio device, in which the mode separation is tripled ($M = 1 + 2$) compared to a laser of the same length with an unperturbed waveguide.

To ascertain the modelocking behaviour of these devices, intensity autocorrelation studies were performed using a commercial 635nm red laser as a two-photon absorption waveguide detector. With devices running pulsed at currents typically $I = 1.5$ to $3I_{th}$ ($P_{peak} \sim 9mW$), an appreciable increase in the peak-to-background ratio was observed when the saturable absorber was reverse biased ($V_{SA} = -1$ to $-4V$), indicating the onset of modelocking operation. It should be noted that a linear component due to unwanted one-