of the unimplanted waveguide is $-8cm^{-1}$ at 1580nm, while it is 5cm$^{-1}$ at 1490nm for the implanted sample. This indicates that no excess loss results from the damage created by the implantation. This decrease could be due to a reduction in Auger effects and intercalation band absorption, as the bandgap wavelength becomes shorter [6]. In addition, the free carrier absorption coefficient is, to a first approximation, proportional to the square of the wavelength and so would be reduced by $\sim$12% over the range of wavelength studied. Another contributing factor is that the guided mode will be more strongly confined within the active region as the wavelength is reduced.

![Graph](image)

Fig. 3 Current/voltage characteristics of pin diodes made from as-grown and implanted material

- - - - as-grown
- - - - implanted

For the ion-induced QW intermixing process to be a useful technique for lateral bandgap control in monolithic integration, it is essential that electrical characteristics of the pin structure not be degraded by the implantation or anneal. Fig. 3 shows the current-voltage characteristics for the as-grown and implanted materials following a 90s RFA at 700°C. We see that both samples have very similar I/V characteristics. The implanted sample shows a slightly higher reverse leakage, which is negligible from the point of view of device operation. Finally, for all the diodes made from the nonimplanted and implanted samples, no breakdown occurred for reverse-biases up to 15V.

In conclusion, we have successfully used phosphorus ion implantation to blue-shift the bandgap of InGaAsP/InP QWs by 90nm in an all-planar process. This technique can be used very effectively to produce transparent waveguides, reducing the absorption from 110$^{-1}$ to only 4cm$^{-1}$, at the original lasers frequency. The current/voltage measurement shows that very little damage to electrical characteristics was incurred by implantation and annealing. The possibility of multiple selective-area bandgap tailoring will allow this QW intermixing technique to be used for monolithically integrating lasers, transparent waveguides and other optoelectronic devices on a single chip using an inherently simple process.

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References


Demonstration of all-optical switching in a symmetric Mach-Zehnder interferometer

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Indexing terms: Optical switches, Light interferometers, Integrated optics

The authors report the observation of ultrafast all-optical switching in an integrated symmetric Mach-Zehnder interferometer using the nonresonant nonlinearity of Al$_x$Ga$_{1-x}$As below the bandgap. A relative switching fraction of $\sim$50% has been achieved using 10ps pulses at a wavelength of 1.55$\mu$m from a synchronously pumped modelocked colour-centre laser.

Introduction: All-optical switching in a single input asymmetric Mach-Zehnder interferometer (AMZI) has been demonstrated previously [1]. A three-input symmetric Mach-Zehnder interferometer (SMZI) device is illustrated in Fig. 1. The operation of the device is similar to that of the AMZI and is as follows: A low power data signal is focused into the central input waveguide such that it splits into two equal parts at the Y-junction power splitter. These two beams then propagate through the two arms of the Mach-Zehnder and recombine constructively at the output Y-junction power combiner and propagate along the output waveguide. A high power control signal is also focused into one of the outer waveguides to produce a nonlinear refractive index change in the waveguide via the nonlinear optical Kerr effect. This produces a phase difference between the two data signals at the output Y-junction causing them to interfere destructively when the phase difference between them is $\pi$ radians. Under this condition, the data signal is coupled into radiation modes and the output falls to zero. Subsequently the device may be used as a modulator.

Fabrication: The material structure of the semiconductor wafer used to fabricate the SMZI is shown in Fig. 2. The AlGaAs layers were grown by molecular beam epitaxy (MBE) on a semi-insulating GaAs substrate. The devices were patterned using standard photolithography techniques and reactive ion etching to form rib waveguides. Also shown in Fig. 2 is the simulated intensity profile of the optical mode launched into the waveguide. This was calculated using a finite-difference implementation of the vector electromagnetic wave equation to give an effective mode area of approximately 15$\mu$m$^2$.  

![Graph](image)

Fig. 1 Schematic diagram of tested device: a symmetrical, three input, Mach-Zehnder interferometer
Experiment. Pulses having a duration of 10ps (FWHM) were generated from a synchronously modelocked colour-centre laser at a wavelength of 1.556μm and a repetition rate of 82MHz. These pulses are then split into two separate pulse trains as shown in Fig. 3. The TE polarised beam forms the high power control pulse and the TM polarised beam forms the low power data pulse. The orthogonal polarisations of the two beams allows them to be separated at the output of the SMZI device using a polariser. An attenuator wheel is placed in the path of the control beam to vary the input power and a chopper wheel is placed in the path of the data beam so that it can be linked to a lock-in amplifier/photodiode arrangement for measurement of any modulation. A delay line is incorporated into the path of the data signal so that the time overlap of the data and control pulses can be altered. Prior to taking measurements, the throughput of the control beam in the device is maximised by manipulation of the input lens (×40 magnification) and the device. Maximisation of the throughput of the low power data beam is achieved via the two mirrors (M) in the delay line path. The output from the device is focused through a polariser and pinhole onto a Ge photodiode using a ×100 magnification lens. Finally, the output of the device is monitored on an infrared camera to check for proper input-waveguide launch conditions and singlemode operation.

Fig. 4 Nonlinear phase-shifts along ~27mm control beam waveguide measured via self-phase modulation spectral broadening

Legend:
- --- zero phase shift at 40MW/cm²
- --- 3π/2 phase shift for 1.23GW/cm² at control waveguide entrance

Results: The linear propagation losses were measured in a straight waveguide to be α = 0.641 cm. The intensity-dependent refractive index change in the straight waveguides was also determined by measuring the spectral broadening of the transmitted pulses caused by self-phase modulation [2]. Self-phase modulation measurements at high input powers showed multi-photon absorption (MPA) to be significant and we estimate the two-photon and three-photon absorption coefficients to be α₂ = 0.3cm/GW and α₃ = 0.64cm/GW², respectively [3]. Using the cross-sectional area of the waveguide as 15μm², we estimate n₂ = 1.3×10⁻⁶cm²/W, which agrees well with previous reports on these AlGaAs waveguides [4].

Next, the nonlinear refractive index changes are measured in the control signal waveguide of the device, again using the spectral broadening technique. Although the length of the control signal guide is similar to that of a straight waveguide, i.e. 27mm, the magnitude of the index change is smaller. This is explained by the losses which occur at points A, B, and C along the waveguide path. At point A ~2.7dB of the control beam is lost into the substrate, at point B there is a much smaller bending loss, and at point C there is, at minimum, a 3dB loss into the substrate [5]. Measurements of the control pulse spectral broadening in the control beam waveguide are shown in Fig. 4 as giving a maximum of 3π/2 phase-shift over the entire length. Using the values given above for scattering losses, MPA, n₁, the waveguide effective cross-sectional area, and the length of each of the Mach-Zehnder sections, the phase shift in the Mach-Zehnder arm alone is calculated to be ~6.8π rad.

Fig. 5 Experimental measurements of data signal modulation. Zero delay refers to data and control pulses being overlapped in time as they pass through device.

Computer simulated curves are also shown to illustrate effects of Gaussian pulse shapes and multi-photon absorption (MPA).

Fig. 5 shows the experimentally measured modulation of the low power data signal caused by the high power control signal. Also shown are theoretical curves for different input conditions. These are derived using eq. 1 to calculate the nonlinear phase shift and eq. 2 to calculate the modulation depth at the output of the Y-junction power combiner.

\[ \Delta \phi = \frac{2\pi}{\lambda} \int n_2 I(\omega) d\omega \quad (1) \]

\[ m = \cos^2(\pi + \Delta \phi/2) \quad (2) \]

where \( \Delta \phi \) is the total phase change in one arm of the SMZI, \( \lambda \) the input wavelength, \( I \) the intensity of the control beam, \( n_2 \) the nonlinear refractive index coefficient, and \( L \) is the length of the SMZI arm (15mm). It can be seen that for the Gaussian shaped pulse used here, the low power wings of the pulse reduce the maximum achievable modulation from 100 to ~75%. We have experimentally measured ~50% modulation, at best, for the maximum phase shift of 0.8π rad along the Mach-Zehnder arm.

As a check on the source of the waveguide nonlinearity the data signal was delayed in time by 500ps with respect to the control pulse, using the delay line. No modulation of the data signal was observed for this condition. Secondly, the colour centre laser was switched from modelocked to continuous-wave operation whilst maintaining the average laser power and with zero delay between pulses. Again, no modulation of the data signal was observed. These observations strongly identify the source of the nonlinearity as being ultrashort all-optical.

In summary, an ultra-fast all-optical, singlemode waveguide, symmetrical Mach-Zehnder interferometer has been demonstrated for the first time in AlGaAs semiconductor material at a commu-
Integrated optical directional couplers in silicon-on-insulator

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Indexing terms: Integrated optics, Optical directional couplers, Silicon-on-insulator

Silicon-on-insulator (SOI) technology offers tremendous potential for integration of optoelectronic functions on a silicon substrate. The authors have demonstrated an integrated 3dB optical directional coupler using SOI rib waveguides. The device has an excess insertion loss of 1.9dB and represents a key component for the realisation of wavelength filters in silicon integrated circuit technology.

Silicon-on-insulator (SOI) technology holds great promise for advancing the performance of CMOS electronic circuits. Major efforts aimed at insertion of this technology are currently in progress and it is expected that SOI-CMOS electronics will be in production in the near future. The unique optical properties of SOI structures offers the ability to integrate photonic devices into CMOS integrated circuit (IC) technology. E.g. single mode waveguides with low propagation loss have been demonstrated in SOI-Si/SiO2 structures [1]. Therefore, significant incentives exist for the development of optical and optoelectronic devices in SOI technology. In this Letter the fabrication of the first directional couplers in SOI technology is reported. The couplers operate at 1.55μm and have an excess insertion loss of ~1.9dB. Using such devices, a variety of components for wavelength-division-multiplexed (WDM) networks can be realised in silicon IC-compatible technology.

The bond and etchback silicon-on-insulator (BESO) wafer had a SiO2 thickness of 1μm and an Si thickness of 5μm. The rib waveguides were formed using a two step reactive ion etching (RIE) process. The first Si3N4 etch was performed at 100mTorr with 250W power for 6min. This was followed by a SiO2:O2:SiF4 at 15mTorr etch at 250W power for 2min. The two step etch was developed to avoid problems associated with polymerisation of the photoresist.

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References

Fig. 1 SEM photograph of rib waveguide coupling region

Fig. 2 Schematic diagram of symmetric directional coupler and rib-waveguide configuration and numerically calculated field distribution of eigenmode

a Schematic diagram
b Rib-waveguide configuration and numerically calculated field distribution of eigenmode

Notation from [1]

Fig. 1 shows the SEM photographs of the coupling section of the directional coupler. The rib waveguide height is 2μm and the width is 3μm. The SiO2 layer can be seen as the light region below the rib waveguides. The separation between the waveguides in the coupling region is 2.5μm. Devices with coupling section lengths ranging from 130 to 400μm were fabricated. Smooth S-bend sections have been utilised to form input and output waveguides with 250μm spacing in order to facilitate coupling using optical fibres as shown in Fig. 2a. The 250μm spacing is also compatible with multi-fibre-array ribbons. Despite the large difference in the refractive index between the silicon and SiO2, single mode propagation in waveguides with large dimension (comparable to the mode of the single mode fibre) can be obtained [1]. In general, single mode condition is satisfied when a+b ≤ 0.3 + rπ[1–r] [see Fig. 2b]. We have used a beam propagation method (BPM) to estimate the waveguide dimensions for single-mode operation. Fig. 2b shows the contour plot of the eigenmode of the rib waveguide. The BPM calculations show that high-order modes, excited by off-axis illumination, decay within distances of a few hundred microns and stable single mode operation is observed. Further, the BPM calculations were used to estimate bending loss against bend radius, using a conformal mapping algorithm. Using this to estimate the minimum S-bend radius (16mm) in the input and output sections of the coupler resulted in the coupler size of ~5mm. This can be improved by optimisation of the bending loss in terms of the waveguide parameters. The propagation loss through straight SOI rib was measured, using the conventional cut-back technique, to be 0.2dB/cm at λ = 1.3μm. This is better than the best published results to date [2, 3]. Fig. 3 shows the measured near-field image a and line scan b of output waveguides for a coupler with 400μm coupling section. The input power is split equally into the two output waveguides. Fig. 4 shows the power split ratio against the coupling length. Comparison with BPM simulations of the entire structure, including the input S-bend, the coupling section and output S-bend sections are also provided. The best fit between the measured data and BPM simulation is obtained for the coupler separation 2.25μm. As can be observed in Fig. 1, the