Polarization-insensitive low-voltage optical waveguide switch using InGaAsP/InP four-port Mach-Zehnder interferometer

TuH3 **2:45 pm**

Polarization-insensitive low-voltage optical waveguide switch using InGaAsP/InP four-port Mach–Zehnder interferometer

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Polarization-independent operation is highly desirable for optical-waveguide switches. It can be realized with directional couplers, digital optical switches (DOS's),[1] and Mach–Zehnder interferometric (MZI) devices. MZI switches[2] have spatially separated regions for electro-optic phase shifting and mode coupling that may permit independent optimization. Multimode-interference (MMI) couplers were recently demonstrated to be promising as polarization-insensitive and fabrication-tolerant power splitter–combiners.[3] Zucker *et al.*[4] realized a polarization-insensitive MZI switch by applying MMI couplers and introducing strain in quantum wells.

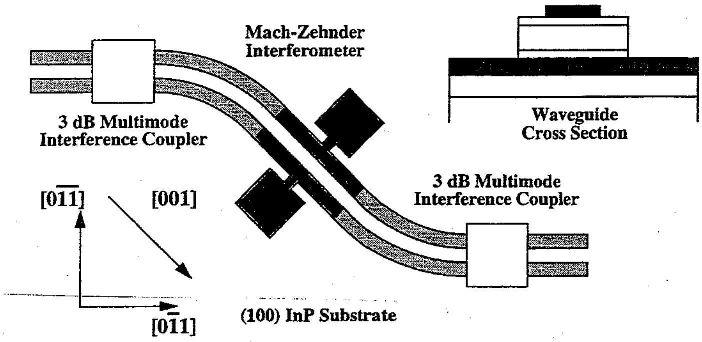
Bachmann *et al.*[5] achieved polarization-independent phase shifts by placing waveguides in the [001] direction on (100) InP substrates in order to eliminate the polarization-dependent linear electro-optic effect and to use the relatively large polarization-insensitive band-edge induced electro-optic effects only. We report here MZI polarization-independent waveguide switches in InP/InGaAsP based on the latter approach in combination with MMI couplers. Polarization-insensitive crosstalk levels better than −16 dB and a switching voltage less than 6 V were measured for electrode lengths of 3 mm.

Figure 1 shows the basic layout of our single-mode switch. The waveguide width is 4 µm in the MZI section and 3 µm in the access waveguides. The 3-dB couplers were realized as MMI couplers[3] with dimensions of 18 × 256 µm.[2] An electrode section of 3 mm oriented in the [001] direction is combined with two 45° curved sections of 2-mm radius so as to align the input and output waveguides perpendicular to the cleavage planes. Lateral offsets are inserted between waveguides with different curvatures in order to reduce mode mismatch. The overall length of the switches is 7 mm.

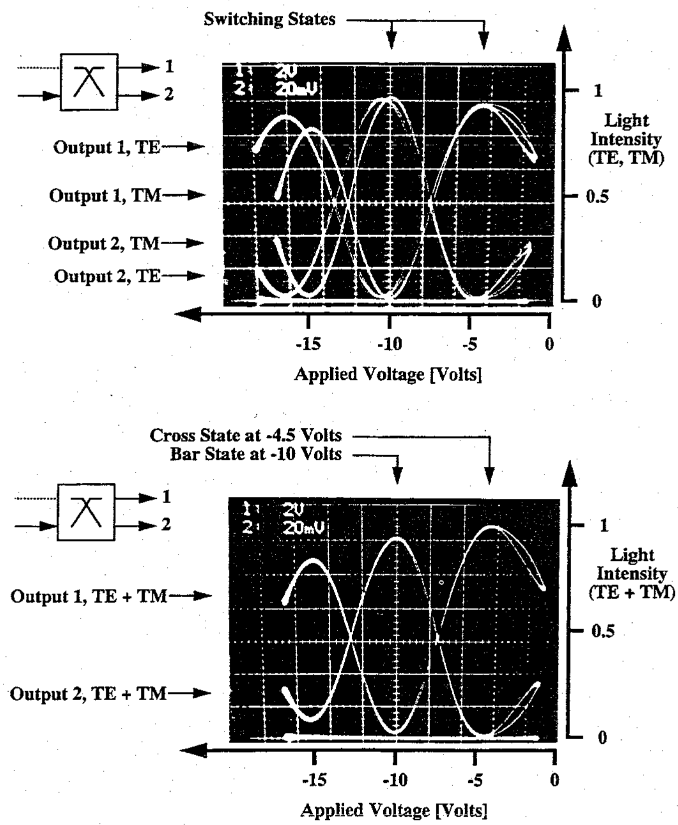
The cross section of the waveguide–p-i-n junction is shown in Fig. 1. A thick InP top and weakly doped layers adjacent to the active InGaAsP waveguide keep the absorption losses low. The doping profile and composition of the quarternary (λ_{gap} = 1.25 µm) were chosen so as to yield switching voltages below 10 V and negligible electroabsorption at the 1.53-µm wavelength.

The layers were grown with metal–organic vapor-phase epitaxy. Waveguides were structured with magnetron-enhanced CH_4/H_2 reactive-ion etching.

Switching curves (Fig. 2), as recorded by coupling light from a 1.53-µm Fabry–Perot laser into and out of the chip with microscope objectives, show an almost polarization-independent response. Cross and bar states are obtained by applying −4.8 and −10.4 V, respectively, to one electrode. At these voltages no electroabsorption (<0.2 dB) was observed. Cross talk is below −16 dB for both polarizations. Net switch loss was determined from the insertion loss measured between microscope objectives, the coupling losses of the cleaved facets, and the propagation losses occurring in the access waveguides (TE: 2.5 dB/cm; TM: 3.5 dB/cm). Total net on-chip insertion losses are 2.5 dB for TE polarization and 3.2 dB for TM polarization. Switch–electrode capacitances are 3 pF.



TuH3 **Fig. 1.** Layout of the polarization-insensitive optical waveguide switch. The insert shows the cross section of the waveguide, which consists of the 0.6-µm InGaAsP (λ_g = 1.25 µm) active waveguide embedded between a 0.8-µm n^--InP buffer layer and a 1.5-µm i-p^--p^+-InP contact.



TuH3 **Fig. 2.** Switching curves of the 2 × 2 InGaAsP/InP MZI switch at λ = 1.53 µm show polarization-insensitive on–off switching between −4 and −10 V with crosstalk better than −16 dB: (a) separate TE- and TM-polarized excitation; (b) combined TE- and TM-polarized (45°) excitation.

Polarization-insensitive and fabrication-tolerant optical waveguide switches have been realized by using rib-waveguide four-port MZI switches. Polarization insensitivity is achieved by placing the phase-shifting waveguides at 45° relative to the cleavage facets on (100) substrates and by using polarization-insensitive multimode-interference couplers for mode coupling. Switching is achieved with 6 V on 3-mm-long electrodes. Polarization-insensitive cross talk of less than –16 dB is achieved for both switching states.

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TuH4 — 3:00 pm

Silica-based optical-matrix switch with intersecting Mach–Zehnder waveguides for larger fabrication tolerances

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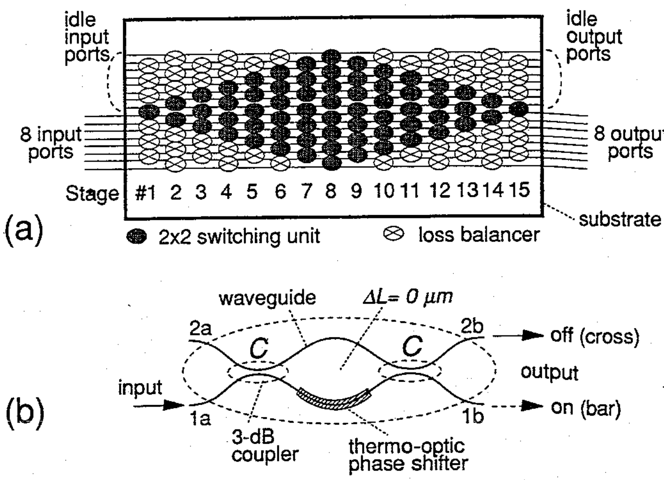
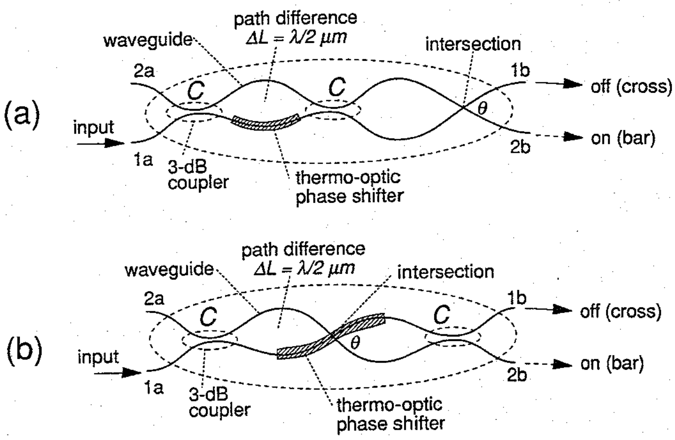
Silica-based strictly nonblocking 8 × 8 matrix switches have thus far been successfully fabricated by integrating 64 thermo-optic (TO) Mach–Zehnder (MZ) switching units on a single Si substrate as shown in Fig. 1.[1,2] The major problem with this type of MZ unit is that the constituent 3-dB couplers must be precisely set at 50% coupling in the waveguide fabrication process. This paper proposes improved MZ geometries for constructing low-crosstalk matrix switches with extremely large fabrication tolerances.

Figure 2 shows two possible configurations for the proposed MZ switching units, which can be used to construct the matrix arrangement shown in Fig. 1(a) with relaxed fabrication tolerances. The proposed units are characterized by a half-wavelength optical path difference ($\Delta L = \lambda/2$) between the two 3-dB couplers, a TO phase shifter on the shorter waveguide arm, and a waveguide intersection either outside [Fig. 2(a)] or inside [Fig. 2(b)] the interferometer region.

An optical signal introduced into input port 1a in the configuration in Fig. 2(a), for example, passes through the interferometer with effectively 0% coupling because of a π phase difference ($\Delta L = \lambda/2$) between the two couplers. This is true even if the coupling ratio C of the two couplers deviates greatly from the ideal 50% value, as long as the two couplers have the same coupling ratio. The successive waveguide intersection in Fig. 2(a) allows the whole optical signal to pass the switching unit in a cross (off) state, irrespective of C. This is in sharp contrast to the conventional MZ unit [Fig. 1(b)], which can achieve the complete cross state only when $C = 50\%$.[1] When



TuH4 Fig. 1. (a) Logical arrangement of strictly nonblocking 8 × 8 matrix switch; (b) configuration of conventional thermo-optic Mach–Zehnder switching unit.



TuH4 Fig. 2. Proposed Mach–Zehnder switching units with waveguide intersection (a) outside and (b) inside the interferometer.

Crosstalk level of 64 switching units	–22 dB ~ –41 dB (average: –29 dB)
Loss budget of 8 × 8 switch:	
1) Waveguide loss (40 cm length)	3.5 dB
2) Intersection loss (0.13 dB/point × 15 stages)	2 dB
3) Loss penalty due to C deviation (50% → 20%)	2 dB
4) Fiber coupling loss (input + output)	1 dB
Total:	**8.5 dB**

TuH4 Table 1. Measured crosstalk characteristics and estimated loss budget for an experimental silica-based thermo-optic 8 × 8 matrix switch.

electric power corresponding to a π phase shift is applied to the TO phase shifter, the unit switches to a bar (on) state. If $C \neq 50\%$, some part of the optical signal remains unswitched in the cross state. In the strictly nonblocking matrix arrangement of Fig. 1(a), this sort of unswitched residual signal can safely pass to the idle output ports without accumulating unwanted cross