A Compact, Scalable Cross-Connect Switch Using Total Internal Reflection Due to Thermally-Generated Bubbles

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Cross-connect switches for connecting optical fibers are important for high speed communications, particularly where wavelength division multiplexing is employed. Commercial optomechanical switches offer low insertion losses but are bulky, expensive and difficult to scale to large numbers of fibers. Commercial thermo-optic switches are far more compact by comparison, but still use a relatively large amount of wafer area, have relatively high insertion losses (e.g. ~ 8 dB in a 4×4 switch) and polarization dependence (frequently ~ 1 dB PDL), and are generally difficult to scale. Free-space silicon micromachined switches are usually limited to small numbers of fibers due to insertion losses incurred from beam divergence. Friction-based wear and difficult optical alignment of all paths simultaneously are problems commonly encountered with free-space micromachined designs.

Our novel, compact single mode fiber cross-connect switch diverts light from one waveguide to a crossing waveguide in a silica planar lightwave circuit (PLC) using total internal reflection (TIR) off the interface between a waveguide and a thermally-generated bubble. Trenches are etched at the waveguide intersections, with one sidewall passing through the point where the waveguide axes intersect. When the trenches are filled with a liquid whose refractive index matches that of the waveguide (the default condition), light is transmitted across a trench into the next colinear waveguide segment as shown in Fig. 1a. When the liquid is displaced by a bubble, the incident light undergoes TIR into the crossing waveguide as shown in Fig. 1b. The concept of a PLC using TIR was demonstrated by Jackel, et al. in 1990[1] using electrolytically-generated bubbles. The device switched light, albeit with rather poor performance. Our devices exhibit much better optical performance since thermal actuation permits use of a fluid with a much closer refractive index match to the waveguide. In addition, our actuators are formed on a separate substrate, allowing independent optimization of the PLC to minimize insertion loss, and improvements in etching technology have yielded much smoother trench sidewalls.

The diamond-shaped feature of Fig. 2 is the PLC portion of a 4×4 device. It contains two 250µm–pitch waveguide arrays intersecting at an angle to support TIR. If no crosspoint along the path of one input fiber is activated to reflect, then the light passes straight through the switch along the original path as a "drop" output. These "drop" outputs, along with the corresponding "add" inputs, allow modular scaling architectures to construct larger switches, as shown in Fig. 3. In contrast, optomechanical and polymer thermo-optic N×N switches do not scale as readily. The switch design reported here is basically polarization-insensitive; only the crosstalk should depend on polarization.

Flame hydrolysis-deposited planar lightwave matrices were fabricated to our specifications by an external vendor. Refractive indexes nominally match those of single mode fiber at 1.55 µm. The core layer is 8 µm high and is centered 25 µm below the top of the upper cladding layer of the as-fabricated PLC. Losses within the waveguides are reported to be approximately 0.1 dB/cm by the vendor. The core layer has been patterned in order to create waveguides 8µm wide at the edge of the switch. In some structures, waveguides adiabatically expand to 16 µm width in order to reduce optical losses while traversing the trench. After the upper cladding deposition, vertical-sidewalled trenches have been etched to a depth of 50 µm. Waveguides approach the trenches at a 60° angle of incidence, which provides for TIR of all rays inside standard single mode fiber. The bubbles used to divert the light are generated using

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immersible heaters constructed using a process based on proven thermal inkjet technology. 70 µm – diameter vertical holes penetrate the silicon heater substrate to supply fluid to the trenches in the PLC. The PLC waveguide matrix is inverted top-to-bottom before being bonded to the actuator circuit.

Initial optical tests were made on PLC structures without actuators. The refractive index of the matching liquid reduces beam divergence, and thus transmission insertion loss, to low levels for our trenches. BeamPROP version 2.1h predicts a 0.2 dB insertion loss for transmission through a 25 µm-wide single trench with 8 µm × 16 µm waveguides. Indeed, fiber-to-fiber losses at 1.55 µm wavelength in test structures containing 32 trenches with these dimensions were measured to be 0.2 dB per trench, agreeing well with theory. Polarization-dependent loss is ≤ 0.02 dB for transmission through four trenches along the "drop" path.

A 4×4 prototype switch was interconnected with single mode fibers in silicon V-groove arrays. Fiber-to-fiber insertion loss was 1.9 to 2.5 dB along the "drop" path, implying approximately 0.55 to 0.85 dB loss per fiber/device interconnection. Insertion loss for reflection off the lowermost crosspoint was 5 dB. For ideal conditions, reflection insertion loss off of an empty trench should be 0.1 dB, so reflection loss was considerably higher than expected, possibly due to nonideal angle (2° from vertical) and placement of the etched trench sidewalls in this device. The same value of reflection insertion loss was measured for reflection at an empty trench as for reflection off a bubble having an end-to-end length approximately 2.5 times the trench width located in the same trench. Extinction (on:off) ranged from 45 to 70 dB for the different reflected paths. Measurements were made without temperature control, so fluid refractive index match and thus extinction were less than ideal. Even so, these results far exceed the single crosspoint performance of interference-based switches.

1. Janet L. Jackel, John J. Johnson and W.J. Tomlinson, "Bistable optical switching using electrochemically generated bubbles", *Optics Letters*, v. 15, n. 24, 1990.

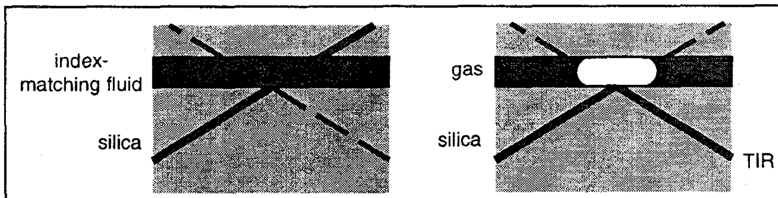

Fig. 1a transmission   Fig. 1b reflection

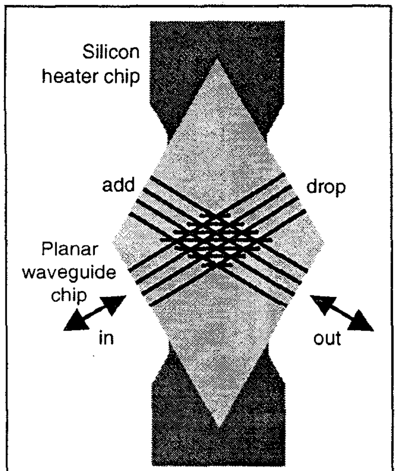

Fig. 2
PLC array with empty trenches
bonded to silicon heater chip

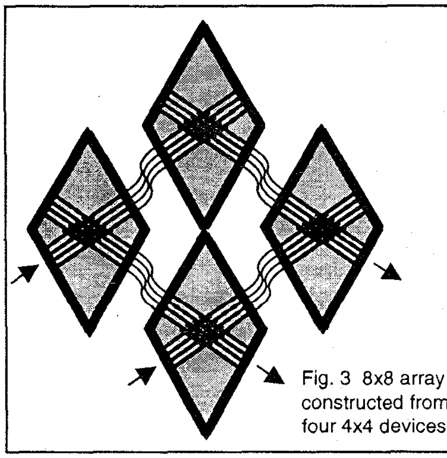

Fig. 3 8x8 array
constructed from
four 4x4 devices