Electrowetting Controlled Non-Volatile Integrated Optical Switch

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Abstract We present the proof of concept of the first non-volatile bistable fiber optic switch combining integrated optics and electrowetting-actuated microfluidics. Design and realization of both EWOD and photonic layer are presented and successful switching of a 2x4 network is demonstrated.

Introduction

Integrated optical circuit technologies enable high-performance, cost-effective and low-loss switch matrices. However, bistable integrated switches with small footprint that hold their state without power consumption have not been demonstrated so far. Optical MEMS switches, mainly based on micro mirrors, can be scaled up to a high number of ports and show low losses[1,2] but no non-volatile commercial solutions exist. Robotic switches using optical fiber connectors are non-volatile but have a large footprint and cannot be used in outside plant conditions[3].

This paper presents the experimental evaluation of the first non-volatile fiber optic switch by combining silicon photonics and EWOD microfluidics, two technologies having reached a state of maturity. Benefits of this novel switching concept are, next to its bistability, the capability of low insertion losses, low crosstalk, high reliability, compact size, outside-plant implementation, low cost and scalability to high port count. The application potential of the switch ranges from datacenters over core networks to access networks.

Working principle

The microfluidic system of the switch comprises a unique bi-phasic liquid combination actuated by electrowetting-on-dielectrics (EWOD)[4] and the optical part consists of an integrated photonic circuit (PIC) based on adiabatic waveguide couplers[5,6]. By changing the refractive index of the cladding material of one of the branches, the coupler changes its state from cross to bar state. Here, the required change of the effective index is achieved by an exchange of the liquid covering one branch of the broadband coupler via EWOD.

If the liquids exhibit appropriate electrical properties, switching with very low power consumption is possible. Bistability is achieved by fluid barriers or matched densities of the liquids. Fig. 1 shows a single switch, its cross-sectional view and the calculated optical field distribution.

Optical substrate

The PIC architecture is based on adiabatic couplers fabricated on a Silicon-on-Insulator (SOI) platform[5]. To enable switching, the bi-phasic fluid system replaces the cladding

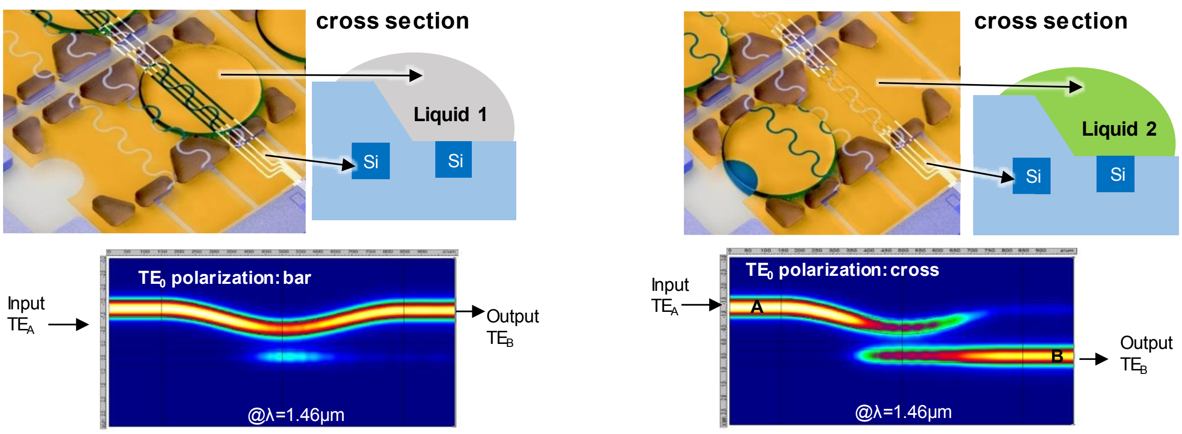

Fig. 1: Working principle of the EWOD controlled liquid switch in cross state (left) and bar state (right).

material of one of the waveguides of the coupler. Consequently, the switching elements are also referred to as liquid controlled couplers (LCC). The LCCs are arranged in a 2x4 configuration path-independent insertion loss (PI-Loss) network[7] (see Fig. 2).

The coupler length is 630 µm and the height of the Si waveguides is 220 nm. To realize exposure of one of the waveguides to the liquid system, the oxide cladding on top of the coupler is locally removed by an etching process. The oxide wall is slanted and the oxide is removed up to the same level as the top of the Si waveguides. To support EWOD driven liquid motion on top of the coupler, the PIC is covered by a dewetting silane monolayer. A SEM image of the cross section of a fabricated LCC is shown in Fig. 3. The slanted etch facilitates the droplet movement and homogenous wetting of the surface.

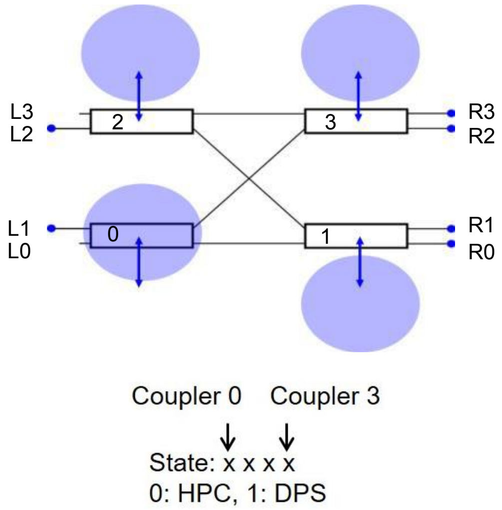

Fig. 2: Configuration of the LCC's in 2x4 network of the SOI PIC (top) and definition of the switch state (bottom).

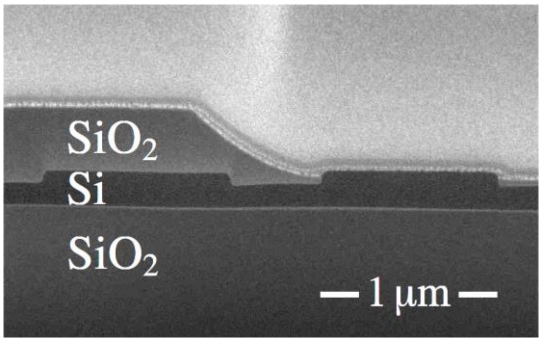

Fig. 3: SEM image of cross-section at middle of coupler.

EWOD substrate

The prototype consists of four cells with one liquid droplet each resulting in one cell per LCC to obtain a 2x4 strictly non-blocking optical switch. The droplet diameter is 900 µm, the length and width of a single EWOD cell is 2300 µm x 1310 µm. The chamber geometry is based on proven design rules known from bi-stable electrowetting display technology[8]. In Fig. 4, the 2x2 fluidic chip design is shown.

The fabrication of the EWOD cell is based on Ordyl dry film resist (DFR) patterning on top of a glass plate containing transparent ITO electrodes and gold conductors covered by an isolating and dewetting coating. Liquid filling is realized by a sand-blasted opening for each cell.

Liquids

Due to the combination of two specific technologies, silicon photonics and EWOD technologies, comprehensive requirements have to be fulfilled by the liquid system. Several bi-phasic fluid systems known for their good electrowetting functionality are unsuited because of their optical properties. Vice versa, obvious optical liquids do not show a satisfying electrowetting performance or they do not meet the required temperature range for outside plant conditions (-40ºC to 70ºC). To guarantee a short optical coupler switch with low crosstalk and insertion loss over the whole telecommunication wavelength range (1260 nm – 1650 nm), a minimum difference in refractive indices of the liquids of about 0.16 is required. Furthermore, the two liquids have to combine polar/non-polar properties, low optical absorption, immiscibility, low melting point and high long-term stability. The liquids found to be suitable for the switch are listed in Table 1[4].

Experimental

The EWOD cell is assembled with the PIC and sealed with a chemically stable UV-curing adhesive. Multi-channel packaged edge-coupling to the PIC is realized by UHNA fibers spliced to SMF-28. Electrical connection to the EWOD

Tab. 1: switching liquids

passive ambient liquid	diphenyl sulfide (DPS)
	triphenyl sulfide (TPS)
electrowetting active liquid	ethylene glycol (EG)
	hydroxy propylene carbonate (HPC)

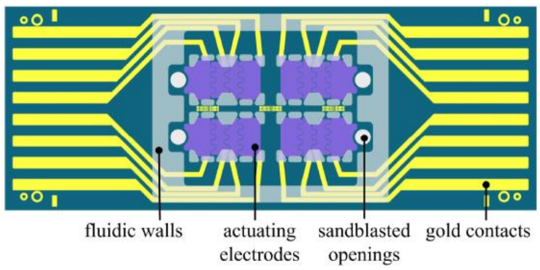

Fig. 4: Top view of the fluidic chip design with overall size of 4.5×12 mm^2.

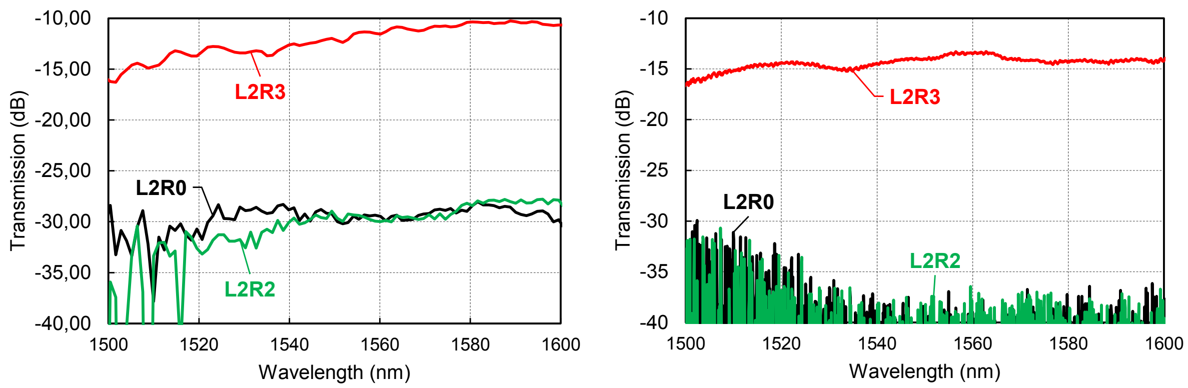

Fig. 7: Transmission of the 2x4 demonstrator in switch state 0010 measured with individual fibers (left) and with fiber arrays (right).

substrate is accomplished by 2x8 channel flex-connectors (see Fig. 5).

An image sequence of the switching process of a single switch is shown in Fig. 6. The bottom left droplet is actuated by an EWOD sequence and a difference in transmission of 15.4 dB is measured at a wavelength of 1550 nm between the ports L1-R3. In Fig. 7, transmission measurements of the 2x4 demonstrator in state 0010 are shown with individual fibers (Fig. 7 left) and after attachment of fiber arrays (Fig. 7 right). The liquids used for experiments are HPC as droplet and DPS as ambient liquid.

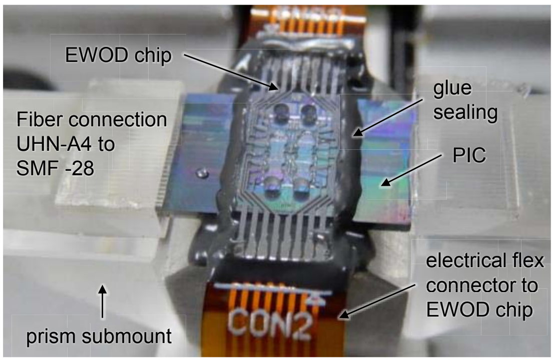

Fig. 5: Photograph of assembled switch device.

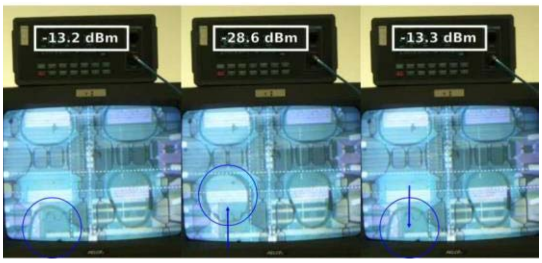

Fig. 6: Snapshots of live video showing the transmission values change when moving the droplet.

Conclusions

A non-volatile bistable photonic switch combining integrated optics and EWOD-driven microfluidics has been introduced. The switching principle is proven by experimental validation and transmission measurements of the assembled 2x4 prototype demonstrator with fiber arrays are presented.

Further research will focus on improvement of the losses of the PIC and the fiber-chip connection by investigating new technology platforms and switch architectures. Investigation of the EWOD part will concentrate on long-term-stability of the system, reduction of the footprint of the EWOD cell and on intelligent electronics for larger arrays.

Acknowledgements

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