A 16 × 16 Non-Volatile Silicon Photonic Switch Circuit

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***Abstract*— A 16 × 16 silicon photonic switch circuit suitable for non-volatile operations has been realized. The switch circuit consists of dilated switch elements with liquid-controlled adiabatic waveguide couplers. The switch with a cross-bar architecture is compatible with a non-volatile electrowetting-on-dielectric system for optical actuation. The measured fiber-to-fiber loss is less than 18.9 dB over the wavelength range from 1500 to 1630 nm. At a wavelength of 1550 nm, the loss is between 8.5 and 17.4 dB depending on the length of the light path. The crosstalk of the switch is better than −50 dB over the wavelength range from 1500 to 1630 nm.**

***Index Terms*— Couplers, integrated optics, liquids, optical fiber communication, optical switches, silicon photonics.**

I. Introduction

NON-VOLATILE optical switches allow zero energy consumption in a steady state. This can be useful in applications where the states of the switches are not often changed and thus they allow to save a large amount of energy. One example of use could be in the remote fiber management in fiber-optic telecommunication networks.

Elementary non-volatile and broadband silicon photonic switches that are actuated by liquids have already been demonstrated in [1]. The switches in [1] consist of an adiabatic waveguide coupler with one of its waveguides exposed to a changeable medium such as a liquid or air. The state of the switch depends on the refractive index of the medium that is present above the exposed waveguide.

The liquid-controlled couplers (LCCs) in [1] were realized on a silicon-on-insulator wafer using deep-UV lithography. This technology together with the relatively short length of the LCCs easily allows the realization of dense non-volatile switch circuits. In this work, we report on the realization of a 16 × 16 switch circuit with LCCs as elementary switches. A dilated cross-bar switch architecture is used to minimize the crosstalk (XT) of the switch. The LCCs used in the switch circuit can be actuated by the displacement of a liquid drop in a second medium. The second medium can be either a liquid with a different refractive index or a gas.

The switch circuit described in this letter is designed for and characterized with liquids that are compatible with an electrowetting-on-dielectric (EWOD) system such as that demonstrated in [2]. The EWOD system in [2] allows the movement of liquid drops inside an ambient liquid and is specifically designed for optical telecommunication switching applications. When the liquid drops in the EWOD system are in their desired positions no energy is needed to keep them in a stable position. The liquid drops remain in a stable position even when the system is mechanically shaked. Furthermore, the proposed EWOD liquids in [2] have good optical properties in terms of refractive index and transmission and are well suited to actuate silicon-based LCCs.

The size of an EWOD chip can be small which makes the EWOD actuation technology well suited for integration with a liquid-controlled switch on an optical chip, such as the 16×16 switch presented in this work. The switch is designed such that it can be readily integrated with an EWOD chip.

II. Design of Switch Circuits

The 16 × 16 switch circuit with a cross-bar switch architecture consists of dilated switch elements (SEs) which can have a reduced XT compared to individual LCCs. The dilated SEs consist of 2 LCCs and a waveguide crossover. A schematic of the switch circuit with dilated SEs and the principle of operation is shown in Fig. 1. The dilated SE is defined to be in the cross or bar state when the two LCCs are in the cross or bar state, respectively. Since the states of the two individual LCCs in a SE are the same for each switch state, the LCCs can be controlled by the same liquid drop as shown in Fig. 1(b) and (c), simplifying the control and minimizing the size.

It is preferable that the XT of a crossover is at least two times better in logarithmic scale than the XT of an LCC in the bar state. If this is fulfilled then the XT of the dilated SE in the bar state at output port O_1, as shown in Fig. 1, is about two times less than the XT of an individual LCC. When the SE is in the cross state then the XT at output port O_2 is identical to that of an LCC. In this situation the leaked light is however guided to an unconnected switch port.

One of the waveguides in the LCC is exposed to a liquid or air by locally removing the oxide cladding above this waveguide. As can be seen in Fig. 1 the oxide trenches of the LCCs in the SE are above the inner waveguides. This reduces the loss of the SE in the bar state as no abrupt oxide-liquid interfaces are present in the light path and the overlap

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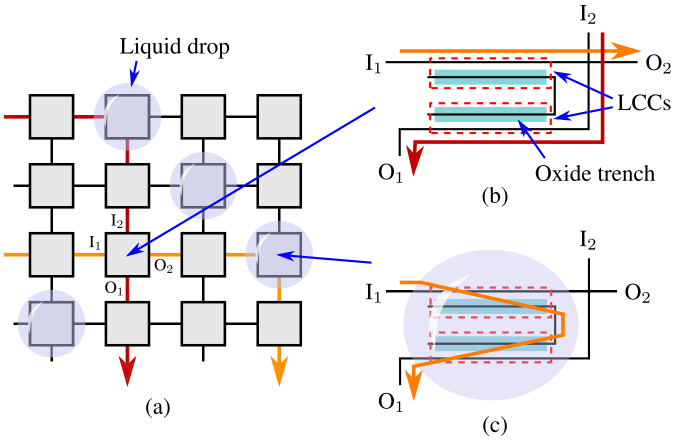


Fig. 1. Schematic of (a) a cross-bar switch circuit with dilated SEs in (b) the bar state and (c) the cross state and with indication of two light paths.

of the light with a potentially absorbing liquid is reduced. Low-reflection grating couplers are attached to the SE ports which are not connected to any other structures. This reduces unwanted reflections.

The LCCs are designed to operate with liquids hydroxypropylene carbonate (HPC) and diphenyl sulfide (DPS) which are compatible with an EWOD system [2]. The LCCs were designed such as described in [1]. HPC is a low-refractive-index and polar liquid while DPS is a high-refractive-index and apolar liquid. The refractive index of HPC is 1.44 and of DPS is 1.60 at a wavelength of 1550 nm and a temperature of 20°C. The bar-state insertion loss (IL) of the designed LCC is similar for air and HPC (or a liquid with a lower refractive index).

To ensure the photonic chip can be integrated with an EWOD chip, the LCCs are arranged to a check pattern (Fig. 1(a)). The LCCs have sufficient space around them to accommodate the barriers needed to confine the liquid drops and to prevent them from mixing with neighbouring drops. The distance between the oxide trenches of the LCCs is 500 μm vertically and 400 μm horizontally. A margin was taken on the dimensions such that the EWOD chip and the photonic chip can be easily integrated and filled with liquid drops. This makes the overall size of the photonic chip relatively large: 19.6 mm × 43.7 mm, and it also increases the total waveguide propagation loss. The size of the switch circuit without fiber edge-couplers is 14.6 mm × 21.1 mm. As such the total photonic chip size can be reduced by more than 40% in future switch generations without compromising the performance, for example by reducing the size of the relatively large area reserved for liquid filling.

III. Fabrication

The fabrication of the switch circuit with LCCs is similar as described in [1]. The top oxide thickness is 1.6 μm and is sufficiently thick to avoid additional attenuation when the chip would be integrated with an EWOD system that comes on top of the optical chip. An optical microscope image of the dilated SE is shown in Fig. 2 with indication of the LCCs and the waveguide crossover. The waveguide widths at the center of the waveguide crossover are 2.8 μm.

A scanning electron microscope (SEM) cross-sectional image at the center of an LCC is shown in Fig. 3. The silicon

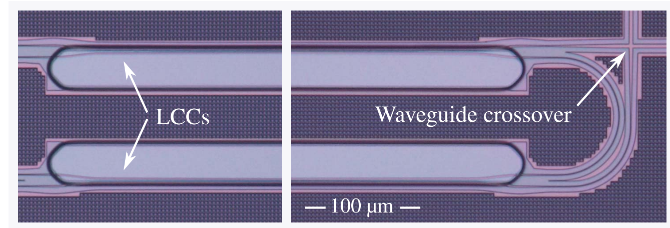


Fig. 2. Optical microscope image of a dilated SE with two LCCs.

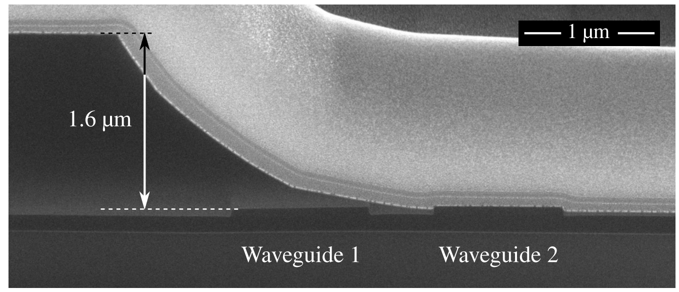


Fig. 3. Cross-section SEM image at the center of an LCC.

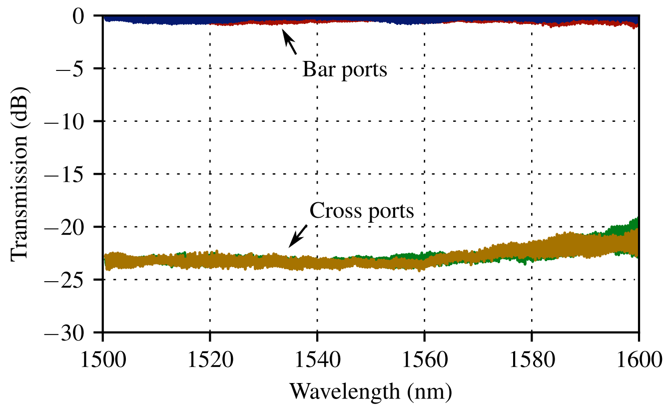
waveguides of the LCC and the interconnecting waveguides have a thickness of 220 nm and are defined by a partial etch of 70 nm. To remove the oxide above the waveguide, a wet etch process with buffered HF is preferred as it is more selective with respect to the silicon waveguide compared to a dry etch process and it results in a slanted sidewall, which is advantageous for liquid movement as explained in [1].

Light is coupled in and out of the chip via fiber edge-couplers. The fiber edge-couplers consist of an inverted Si waveguide taper covered by a silicon oxynitride overlay waveguide similar as described in [3]. The advantage over fiber edge-couplers with polymer waveguides is that they are mechanically more robust and allow high-temperature processing steps which simplifies bonding with an EWOD chip and hermetic sealing. The chip facets are polished to obtain straight chip facets such that the chip can be integrated with fiber arrays to obtain a low fiber-chip coupling loss at all optical ports.

IV. Characterization and Discussion

Elementary structures that are part of the switch circuit are first characterized separately to get insights in the loss contribution to the complete switch circuit. The IL of a waveguide crossover is measured to be less than 0.3 dB over the wavelength range from 1500 nm to 1600 nm and the XT is −55 dB at a wavelength of 1550 nm. The transmission of the waveguide crossovers is obtained from multiple structures connected in series. The measured propagation loss of the interconnecting waveguides is less than 0.7 dB/cm over the same wavelength range. For the characterization of all the elementary structures, the minimum wavelength is restricted by the wavelength range of the tunable laser and the maximum wavelength by the bandwidth of the fiber grating couplers connected to the test structures.

The transmission of an 820-μm-long LCC in the cross and bar states is shown in Fig. 4. The liquids HPC and DPS were used to characterize the bar and cross states of the LCC,



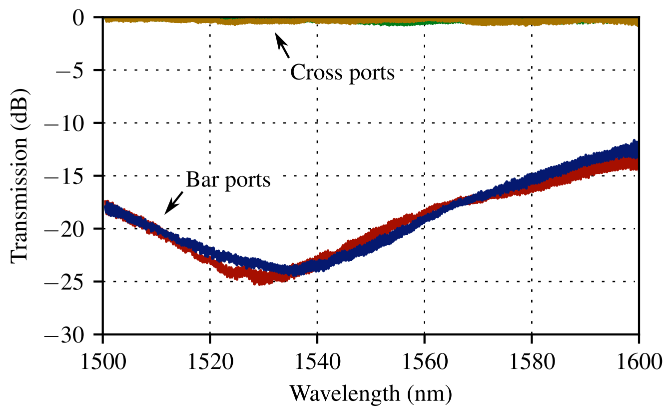


Fig. 4. Transmission of an 820-μm-long LCC in (a) the bar state and (b) the cross state.

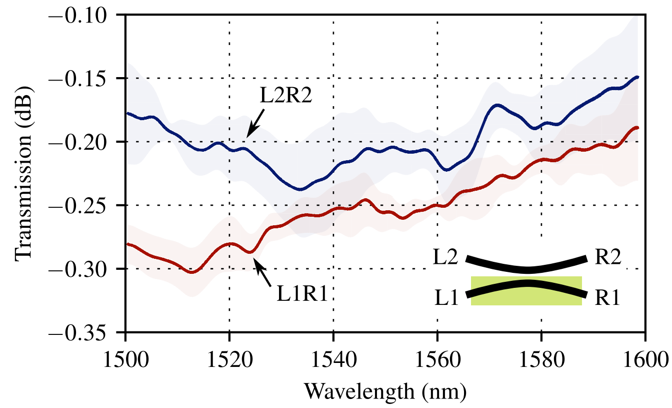


Fig. 5. Bar-port transmission of the LCC in the bar state with light going through the shielded waveguide (in blue) and through the waveguide exposed to the liquid HPC (in red).

respectively. The XT of the LCC is less than −20 dB in the bar state and less than −12 dB in the cross state over the wavelength range from 1500 nm to 1600 nm. Fig. 5 shows the bar-port transmission of the LCC that is obtained from the linear regression of multiple LCCs connected in series. The figure also shows the standard error. From Fig. 5 it can be inferred that the IL of the LCC in the bar state with light going through the waveguide exposed to the liquid is higher than when light is going through the shielded waveguide, especially at the shorter wavelengths. The IL is less than 0.24 dB when light is going through the shielded waveguide and less than 0.30 dB when light is going through the waveguide exposed to the liquid. It is therefore better to connect the LCCs in the dilated SE such that when in the bar state light goes through the shielded waveguides as shown in Fig. 1(a).

The IL of a single fiber edge-coupler is less than 2.2 dB over the wavelength range from 1500 nm to 1630 nm. The characterization of the fiber edge-coupler is done with Nufern UHNA4 fibers, which are high-NA fibers with a mode-field diameter of 4.0 μm at 1550 nm (NA = 0.35), fusion spliced to G.652 fibers (Corning SMF-28) with a mode-field diameter of 10.4 μm at 1550 nm. An index-matching liquid is used with a refractive index of 1.42 at a wavelength of 1550 nm. The IL of the fiber edge-coupler includes the loss of the fusion-spliced connection between the SMF-28 and UHNA4 fiber which is about 0.3 dB.

An overview of the loss of each component in the switch, the expected total losses of the shortest and longest light paths, and the contribution to the total loss is given in Table I at a wavelength of 1550 nm. The reported losses are obtained from test structures as described above. The interconnecting waveguide loss does not include the waveguide loss of the SEs. Referring to Table I, the total loss of the 16 × 16 switch is expected to be between 6.0 dB for the shortest path with 1 SE, up to 18.4 dB for the longest path with 31 SEs, at a wavelength of 1550 nm. The largest contribution to the total switch loss in the longest path is due to the bar state SEs, followed by the fiber edge-couplers. About half of the loss of a SE in the bar state (0.4 dB) is due to the LCC (0.2 dB), the other half is from the waveguide crossover (0.2 dB). Multi-mode interference (MMI) crossovers and subwavelength grating crossovers can reduce the loss below 0.1 dB [4], [5]. Together with further improvements in the processing and design, this indicates it should be possible in the future to reduce the loss of the SE in the bar state down to 0.2 dB.

The characterization of the full switch circuit is done by dispensing a drop of DPS above a SE to redirect the light between the horizontal and vertical directions. No liquid is present above the other SEs in the same light path. Fig. 6 shows the transmission of a few light paths as a function of the number of SEs in its path. In the same figure the expected transmission from the individually characterized components in Table I is shown in solid lines. The transmission is obtained with individual fibers. For all paths the total IL is lower than 17.4 dB at 1550 nm and lower than 18.9 dB over the measured wavelength range from 1500 nm to 1630 nm. The smallest IL of the 16 × 16 switch at 1550 nm is 8.5 dB. The IL of the SE in the bar state is similar for HPC and air and therefore a similar IL of the 16 × 16 switch is expected for both media. The wavelength-dependent loss (WDL) of the switch circuit is mainly due to the WDL of the LCCs in the cross state. It is expected that the WDL can be reduced with an improved fabrication. The loss per SE in the bar state obtained by a linear regression from the switch transmissions in Fig. 6 is less than 0.29 dB over the wavelength range from 1500 nm to 1630 nm, with a standard error of 0.02 dB.

The XT of the switch is defined as $10\log_{10}(P_O/P_I)$, where P_I and P_O are the input and output powers of the switch with one input port that is active. The XT is obtained by

TABLE I

LOSS CONTRIBUTION OF THE ELEMENTARY COMPONENTS IN THE SWITCH CIRCUIT AT A WAVELENGTH OF 1550 nm. THE SHORTEST AND LONGEST LIGHT PATHS CONTAIN THE SMALLEST AND LARGEST NUMBER OF SEs, RESPECTIVELY

Component	Loss per unit	Number of units in		Total loss (dB) in		Contribution to total loss
		Shortest path	Longest path	Shortest path	Longest path	in longest path (%)
SE in the bar state	0.4 dB	0	30	0.0	12.0	65
- LCC	0.2 dB					
- Crossover	0.2 dB					
SE in the cross state	0.6 dB	1	1	0.6	0.6	3
Interconnecting waveguide	0.6 dB/cm	3.0 cm	3.7 cm	1.8	2.2	12
Fiber edge-coupler	1.8 dB	2	2	3.6	3.6	20

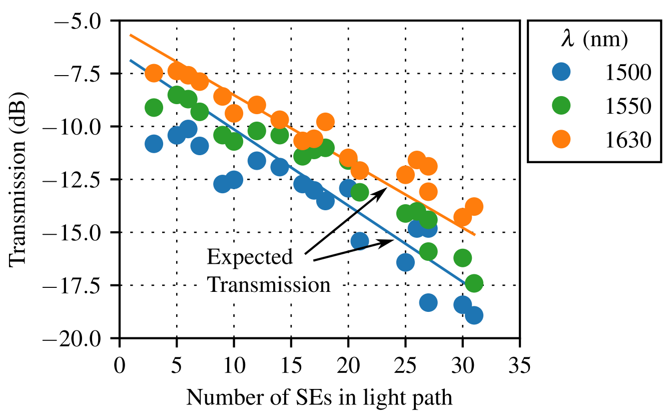


Fig. 6. Transmission of the 16 × 16 switch for different light paths and at different wavelengths. Solid lines represent the expected transmission obtained from characterized individual components.

measuring the XT of part of the switch circuit that gives the worst XT. This part of the cross-bar switch network has the smallest number of SEs in a light path. We restricted the study to all port combinations of a subcircuit with 4 input ports and 6 output ports and to the wavelengths of 1500 nm and 1630 nm. Either HPC or air is present above all SEs. Based on these measurements we expect that the highest XT retrieved from this small subcircuit is a good representation of the highest XT of the complete 16 × 16 switch.

The XT of an LCC in the bar state is different when HPC or air is above the exposed waveguide. The measured XT of the switch is less than −50 dB over the wavelength range from 1500 nm to 1630 nm when the bar state of the SEs is obtained with HPC. The theoretical XT of the switch with liquids HPC and DPS, based on the measured IL and XT of the individual components, is less than −53 dB at a wavelength of 1550 nm. This is in good agreement to the measured XT.

When the bar state of the SEs is obtained with air then the XT of the switch is less than −63 dB over the wavelength range from 1500 nm to 1630 nm. This is 13 dB lower than when the bar state is obtained with HPC which is due to the lower XT of the LCCs when covered by air. An EWOD liquid actuation system with liquid drops surrounded by air and that can be integrated with an optical chip is however much more difficult to realize. The highest XT of the switch with SEs covered by air or HPC was obtained at a wavelength of 1630 nm.

V. CONCLUSION

A 16 × 16 liquid-controlled silicon photonic switch circuit is realized with LCCs as elementary switches. The realized switch can be readily integrated with an EWOD system to obtain a non-volatile optical switch system with zero energy consumption in a steady switch state.

The total fiber-to-fiber loss of the switch is less than 18.9 dB over the wavelength range from 1500 nm to 1630 nm. At 1550 nm the loss of the switch with a cross-bar architecture varies between 8.5 dB and 17.4 dB depending on the length of the light path. The switch contains dilated SEs with a bar-state IL less than 0.29 dB over the wavelength range from 1500 nm to 1630 nm. The dilated SEs are a viable solution to obtain a low XT. The measured XT of the EWOD-compatible switch with liquids HPC and DPS is better than −50 dB over the wavelength range from 1500 nm to 1630 nm.

The realized switch has a good performance over a wavelength range of 130 nm. However, for use in optical telecommunication networks, the loss of the switch circuit needs to be further reduced and the bandwidth needs to be increased. When considering SiN as a platform for the LCC fabrication we achieved a broader wavelength range of operation with a low loss suitable for telecommunication applications and operation up to 70°C [6]. The long-term stability of the liquid system used for switching has to be investigated in more detail.

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