Demonstration of a 4 × 4-port Self-configuring Universal Linear Optical Component

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Abstract— We present our work on reconfigurable, general-purpose linear photonic circuits. Photonic integrated circuits today resemble the very specialized application specific integrated circuits (ASICs) rather than general-purpose CPUs or highly flexible field-programmable gate arrays (FPGA). Reprogrammable optical circuits could dramatically reduce the time to application or prototype a new optical chip. We will discuss the possibilities of such circuits, and present a working implementation of a 4 × 4-port universal linear circuit implemented in silicon photonics. We demonstrate the circuit performing two distinct linear operations by changing the software algorithms that controls the circuit.

1. INTRODUCTION

Silicon photonic components offer an exciting future for a number of different applications. The high contrast of silicon allowed the reducing of the size of integrated optical components. It enabled the creation of dense and complex photonics circuits. Like with electronic *application specific integrated circuits* (ASIC), such circuits are often the most efficient in terms of footprint, power consumption and optical transmission. However, because they have to be created for one specific function, the development often requires a long time and several costly fabrication iterations. An update or upgrade of the system also requires an updated version of the chip. The opposing proposition is to use photonic circuits that consist of a large network of similar or identical unit cells, and where the functionality can be defined by adjusting the optical paths through the network. In concept, this resembles a *field programmable gate array* (FPGA) in electronics [3].

A great number of optical operations such as coupling structures, frequency filtering, optical delays, switch networks and quantum optics operations can be implemented using linear optical devices [1, 2]. A generic and reconfigurable optical linear device is a device that would implement any linear operation between its inputs and outputs by changing its internal configurations. This approach introduces a versatile and flexible linear optical component that can be configured to perform complex different optical applications. Such device can be reusable, and scalable if its internal connectivity is reprogrammable. Using internal real-time feedback signals the circuit can also adapt itself to changing input signals and external conditions, and a circuit can be made scalable and resilient to failure of one or more elements.

The implementation of reprogrammable photonic functions requires more than a network of elemental optical building blocks. The photonic circuit needs to have many actuators and monitors, accompanied by (analog) driver and read-out electronics, digital feedback loops for the individual elements, and a software stack to (re)program the overall functionality. This *Photonics-Analog-Digital-Software* stack (PADS) will inherently have a larger footprint and a higher power consumption than a specialty photonic circuit.

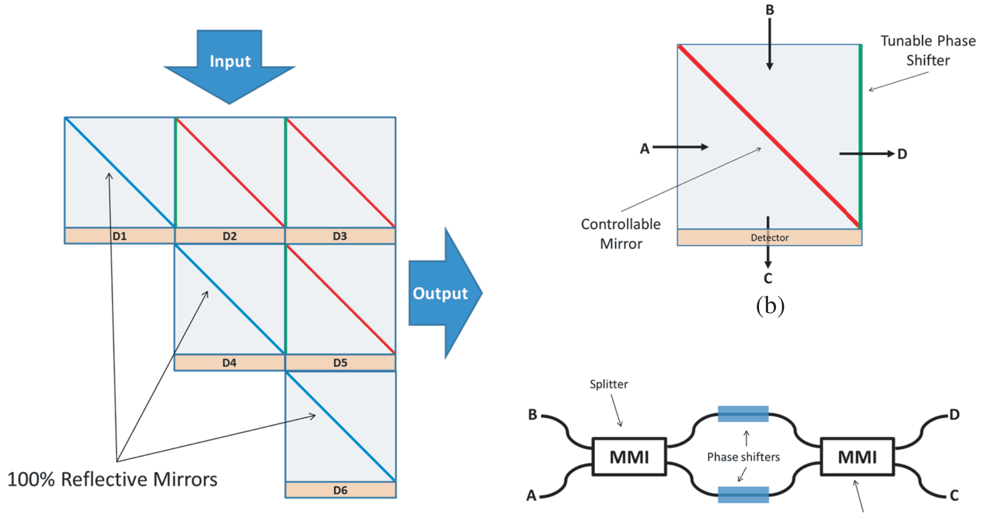
2. RECONFIGURABLE LINEAR CIRCUITS

A concept of a circuit that can perform any linear operation between N input and N output ports was introduced by David Miller [1]. In Miller's concept, optical phase shifters and controllable mirrors are used to achieve this goal, and local control algorithms are proposed to achieve the overall objective of maximizing power coupling to a single port, by driving optical phase shifters and reading the power from (transparent) photodetectors, governed by feedback loops. The objectives for the local algorithms are in turn controlled by a global configuration scheme. This allows independent actuation of the devices and the monitor readout, performing real time adaptations to the circuit.

To facilitate scalability we should aim for a device with small footprint, allowing it to scale it to multiple devices per circuit. To keep lower power consumption it is key the use of efficient optical phase shifter and photodetectors. Preferentially we should implement the device using well tested off-the-shelf components to guarantee the stability of the final circuit.

3. DESIGN OF A 4 × 4-PORT CONFIGURABLE LINEAR CIRCUIT

The discrete form of the proposed reconfigurable universal linear device is visualized in Fig. 1(a). In this schematic the red elements are mirrors with controllable reflectivity while the green lines are transparent phase shifters. The apparatus can be perceived as a caccade of single unit cells, as illustrated in Fig. 1(b). Each of these unit cells implements a 2 × 2-port configurable linear device.



(b)

(a) (c)

Figure 1: (a) A discrete representation of the proposed device. Diagonal red lines represents mirrors with controllable reflectivity. Vertical green lines represent controllable phase shifters. (b) Representation of an individual cell of the circuit with two inputs (A and B) and two outputs (C and d). (c) Mach-Zehnder implementation of the building block cell with two inputs (A and B) and two outputs (C and D).

We implemented the proposed device as a circuit in IMEC's passive silicon photonics platform [4]. We only used established building blocks from the supplied *process design kit* (PDK). To implement the reconfigurable circuit in a hierarchical way we first constructed the basic unit cell using a symmetric, thermally tunable, 2 × 2 *Mach-Zehnder interferometer* (MZI), as shown of Fig. 1(c). This is equivalent to a combination of a tunable reflector + phase shifter. The MZI is implemented using standard 2 × 2 *multimode interferometers* (MMI) as splitter/combiner and strip waveguides as its arms. We designed heaters for later post-processing on top of each arm of the MZI to allow individual thermo-optical phase tuning of the two arms. A differential drive between the arms will induce a complementary amplitude modulation at the 2 outputs, which will make the device behave as a controllable mirror. Common-mode driving of the heaters will introduce the same phase shift in both outputs.

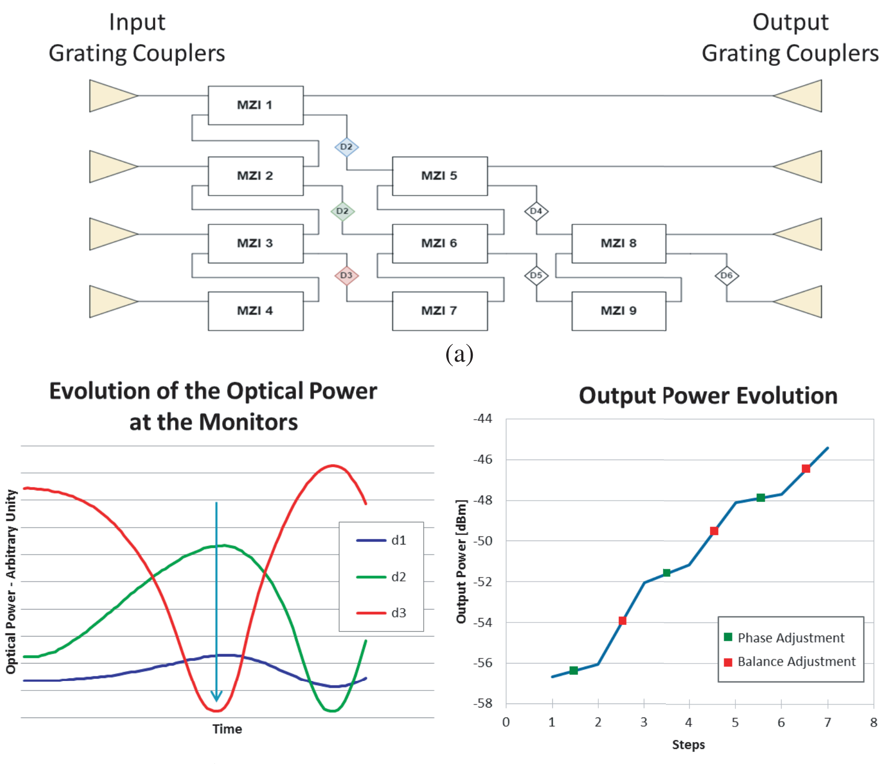
To collect information for the feedback control loops that drive the phase shifters, we need to add a 'transparent' photodetector at the outputs of the MZI. The detectors need to be transparent (that is, have a high transmission) because otherwise the overall power penalty for the circuit will become tool large: the light that goes 'through' the detectors will proceed to the next row in the circuit.

To implement the transparent photodetectors in a passive silicon platform, we tapped a small fraction of the light from the waveguide using a short directional coupler and connected it to a grating coupler to be used as monitor. An external infrared (IR) camera was used to simultaneously detect the light emitted by the grating couplers monitors of the many unit cells.

We designed our device as a network of of these 2 × 2 MZI building blocks (Fig. 2(a)). The circuit was designed using the IPKISS toolset from Luceda Photonics [5]. The MZI and the circuit were simulated using the Caphe circuit simulator, which is integrated with IPKISS.

The monitor grating couplers, used for the feedback readout of the circuit, are grouped together in a small area, which makes possible to read all the monitors in a single frame of the IR camera.

The optical input and output are possible using vertical coupled grating couplers placed in a linear array. This also allows the use of a fiber array to be connected to the inputs and outputs.



(a)

(b) (c)

Figure 2: (a) The 4 × 4-port circuit implemented with 4-port Mach-Zender interferometers. $d1$ to $d5$ are detector used to monitor the behaviour of the circuit. (b) The behaviour of the detected $d1$, $d2$ and $d3$ during an intermediate tuning phase of the circuit. (c) Evolution of the power at the output of the after each discrete steps of [missing word here] when the circuit is operating as a beam coupler device.

The electrical connections are routed to a single row of 100 × 100 µm electrical pads, allowing the contact by a probe card.

The optical circuit is realized in the passive SOI platform of IMEC, Belgium, through the Europractice MPW service [4]. The silicon waveguides are 220 nm thick, and an additional 2 µm of oxide is deposited as a top cladding. On these, we processed simple resistive titanium heaters with gold wiring using a liftoff process.

4. EXAMPLE OF APPLICATION: A SELF-CONFIGURING BEAM COUPLER

To operate the circuit as a beam coupler we illuminate the input(s) of the circuit and monitor the power at the output while the algorithm adjusts the balance and the phase shift of the MZIs in the circuit. We used a laser source at 1550 nm and beamed light at the multiple inputs of the circuit (grating couplers) from a single fiber by flood illumination. It resulted in an arbitrary amount of light entering the circuit through each of the grating couplers.

An infra-red camera is mounted on top of the circuit for monitoring the grating couplers that were used as power monitors. The heaters are driven using a current source equipped with voltage meter to measure the power consumption. The information about the electrical power applied at each heater is used to perform a fine control on both the balance and the phase modulation. The light collected from the output of the circuit is redirected to a power meter. The implemented setup is represented in Fig. 3. The overall system is controlled by Python scripting.

The plot in Fig. 2(b) shows the evolution of the power from the monitors $d1$, $d2$ and $d3$ during the tuning phase of the MZI $m3$. The circuit changes the power balance at $m3$ in order to minimize the power at $d3$ (red). Minimizing the power at $d3$ will increase the output at $d2$ and $d1$ (blue and green), as can be seen in Fig. 2(b). The plot in Fig. 2(c) shows the evolution of optical power at the output of the circuit after each step in the [missing word] process. As we are using flood illumination to shine light at the inputs of the circuit, it results in a small phase difference between the inputs of the circuit. Because of that we notice that the the contribution in the optical power

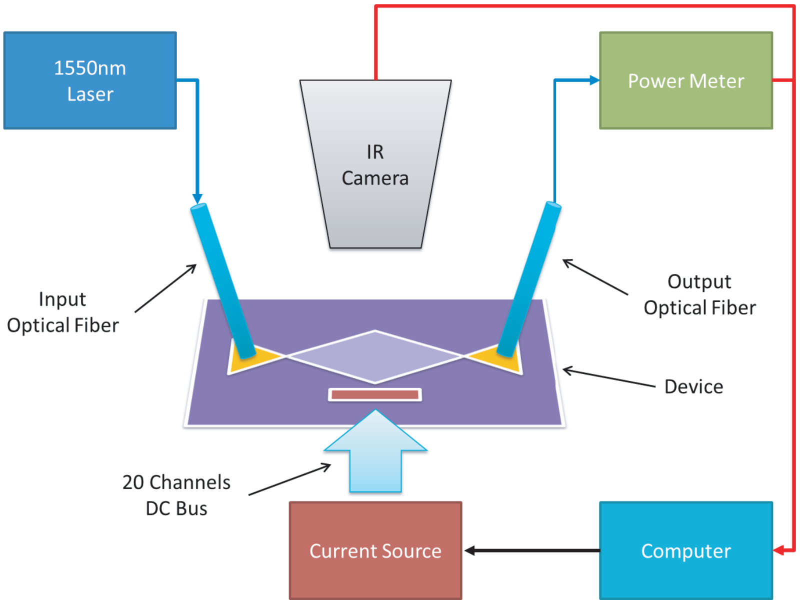


Figure 3: Measurement setup. Fibers are used for optical input and output while an IR camera is used to capture the in-circuit monitors. Heaters are driven using a 20-probe array.

increment is noticeably larger when a balance adjustment is performed (Fig. 2(c) green) when compared to a phase adjustment (Fig. 2(c) red).

5. CONCLUSION

Reconfigurable and adaptive multi-ports optical linear devices can be seen as a building blocks to complex but flexible optical circuits. We have demonstrated an operational 4× 4-port universal linear circuit operating a beam coupling function that maximizes the optical power at the output of the circuit. The circuit adapts itself to an arbitrary input by following an algorithm based on local feedback loops.

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