Experimental Demonstration of Automatic Reconfiguration and Failure Recovery of Silicon Photonic Circuits

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Abstract *Automatic reconfiguration with failure recovery of photonic functions has not been experimentally demonstrated as far as we know, which is important for real-time operating programmable photonics. Here we experimentally demonstrate automatic reconfiguration and failure recovery for silicon photonic circuits by bacterial foraging algorithm.*

Introduction

Automatic failure recovery is a very important issue in real time systems such as processors and networks, to guarantee smooth and quick recovering from link and switch failures[1]. With wide deployment of integrated photonic devices for optical interconnects in communication and computing systems, considering failure recovery for these photonic devices becomes necessary in system design, which is also meaningful for system maintenance to save cost and time. For recovering photonic devices from failure, one prerequisite is that the device itself offers nonunique configuration for one target function. Specifically designed photonic devices with backup function or programmable integrated photonic circuits that provide circuit redundancy can satisfy this requirement. As a new paradigm in designing photonic devices, programmable photonic circuits are attractive as one general-purpose platform for various applications[2], enabling great system flexibility, and meanwhile, failure recovery is also achievable due to reconfigurability[2],[3]. So far, many works have been given to automation for self-reconfiguration and self-routing[2],[3]. Despite of self-healing capabilities were mentioned possible for these programmable circuits, as far as we know, automatic self-failure-recovery has not been experimentally demonstrated yet for silicon photonic circuits.

Even though manually searching another configuration sometime is possible for simple applications with simple topologies, automation of failure recovery is highly required and equivalently important as automatic function reconfiguration in real time systems. Manual route searching could be done by ideal path analysis, but in real devices the nonideal components due to fabrication errors make it difficult to predict the optimal configurations even using pre-calibrated data. The pre-calibration is usually done for components one by one without including possible influences from environmental changes when all components are used; thus, the reconfiguration set in term of these obtained data could severely deviate from estimation. More importantly, if operating large numbers of tuning components to achieve high-complexity functions, manual setup is almost impossible for both reconfiguration and failure recovery. In this work, we experimentally demonstrate both self-configuration and self-failure-recovery for a silicon photonic circuit by bacterial foraging optimization (BFO) algorithm. This device can be reprogrammed for different applications such as classification computing[4],[5]. It consists of same components as other photonics circuit[6],[7]; thus, this method could be also applied to other similar photonic devices. To the best of our knowledge, this work for the first time experimentally demonstrates automatic failure recovery in a black-box way for silicon photonic circuits without knowing where the error happens and without using any on-chip monitoring devices.

Experiment description

The device we used to demonstrate automatic reconfiguration and failure recovery is shown in Fig. 1(a). Actually, this device was originally proposed to implement classification computing[4] and we have demonstrated implementing different machine learning classification tasks on this single photonic chip[5]. It is also possible to program this device for other functions, such as a 1×8 path router and an arbitrary splitter. In this work, we take a 1×8 path router as the target function for demonstrating self-reconfiguration and self-failure-recovery. The topology of this device can be refered to in Refs. [4,5]. This device was fabricated on a 220-nm silicon-on-insulator wafer with a 3-μm bottom oxide layer at the AIST-SCR 12-inch CMOS platform[8] by utilizing liquid-immersion ArF photolithography. The chip size is 5 mm × 1.3 mm. It consists of Mach-Zehnder interferometers (MZI) and phase shifters, all of which are thermo-optic ones using TiN micro heaters. An enlarged MZI unit is shown

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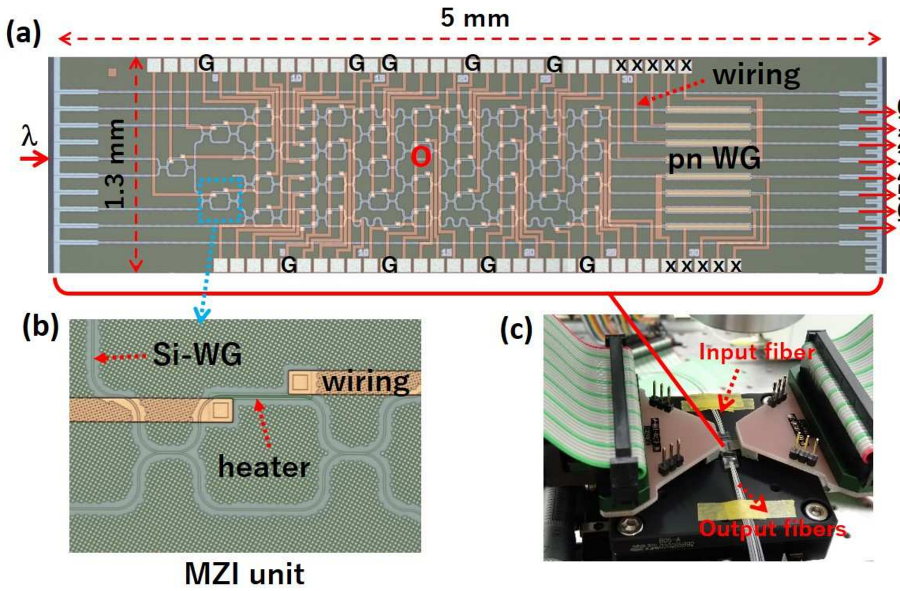

Fig. 1: (a) Microscopy of the fabricated device. Electrical pads marked by G indicates the ground pads and those marked by x were not used in this experiment. The mark "o" shows the MZI we will manually break its current during reconfiguration to simulate failure. (b) An enlarged MZI unit. (c) Image to show the device under measurement.

in Fig. 1(b), showing the Si-wire waveguide (WG), AlCu wiring, and TiN heater on one arm (only upper arms were fabricated with heaters to reduce electrical pad numbers). Other fabrication details are same as our previous works[6].

For optical coupling, inversely tapered spot-size converters were fabricated at both facets and the chip was packaged with fibre arrays. The coupling loss is about 2.5 dB per facet. The fibre array packaged chip under measurement is shown in Fig. 1(c). This chip was not electrically packaged, and we use two 40-pin probes to contact with the electrode pads. Note that at the output straight waveguides the *pn* waveguides with horizontal *pn* diode embedded were not used in this experiment; thus, the pads marked by "x" in Fig. 1(a) can be neglected here.

The laser light at 1.53 μm wavelength was input to the port as indicated in Fig. 1(a) after being tuned to TE polarization. The output optical powers from eight ports were measured by a photodetector equipped with a port-selectable switch. A computer read these powers and controlled two 40-channel dc electrical sources that were connected to two 40-pin probes through flat cables. In Ref. [3], genetic algorithm and particle swarm algorithm were used for self-configuration of programmable photonic circuits. In this work, we employed BFO algorithm to realize self-configuration and self-failure-recovery for the chip shown in Fig. 1(a). This algorithm is also a global optimization one, which does not need the prior knowledge regarding topology and the pre-calibration data of every component. We reported simulation works using this algorithm to reconfigure universal circuits[9] and calibrate large-scale matrix switch[10]. We have explained the algorithm principle in detail in Refs. [9,10] and this work is an experimental verification of this algorithm to realize multipurpose application for silicon photonic circuits.

Self-reconfiguration experiment

We take the 1×8 path router as the target function to demonstrate self-configuration. The device works as a tunable interferometer that transforms the input light to one target port (to be maximized in optical power). The optimization is to search the voltage (V) distribution among all phase shifters to minimize the mean squared error (MSE) between normalized power vector $\boldsymbol{y}$ ($=p_i/\Sigma p_i$) and target vector $\boldsymbol{y_t}$ (=1 for the target port, =0 other else). Figs. 2(a)-2(c) show the experimental results of automatic reconfiguration for the target ports 1, 5, and 7, respectively. For each of them, the optical power gradually increases with optimization (one loop means one-time voltage change), almost equal to the total power that sums up all ports, and the powers at other ports become nearly zero. All MSE errors shown in Fig. 2(d) are gradually decreased to ~0.001. We have confirmed that all ports can be set to the maximum power automatically within 1500 loops. Switching between reconfigured states requires external memory to save the learned voltages, which cannot be achieved by simply switching a single MZI.

Self-failure-recovery experiment

We take the same target function as we did above to demonstrate self-failure-recovery experiment. Here we choose the port 3 as the target port that is not shown above. During the automatic reconfiguration by running BFO algorithm to maximize the power at the port 3, we manually broke the current for the MZI marked by "o" in Fig. 1(a) and checked whether the algorithm can automatically find another valid voltage state. Fig. 3(a) shows the results of both automatic reconfiguration and failure recovery for the target port 3. As seen, at beginning, the reconfiguration proceeded similarly as seen in above reconfiguration experiment and almost completed after ~500 loops. At the time, we manually broke the current of the "o" MZI. Then, the power at the port 3 was suddenly decreased to its 1/5. Meanwhile, the MSE was also suddenly increased, as shown in Fig. 3(b). With this failure, we did not interfere the optimization progress any more and the algorithm automatically recovered the power at the port 3 to the same level as before introducing the failure with ~2000 loops. In this work, the light does not follow a single path to the target port since the MZIs work in middle states. All-off or all-on reconfiguration is also possible provided that two phase shifters are fabricated on both arms of MZI.

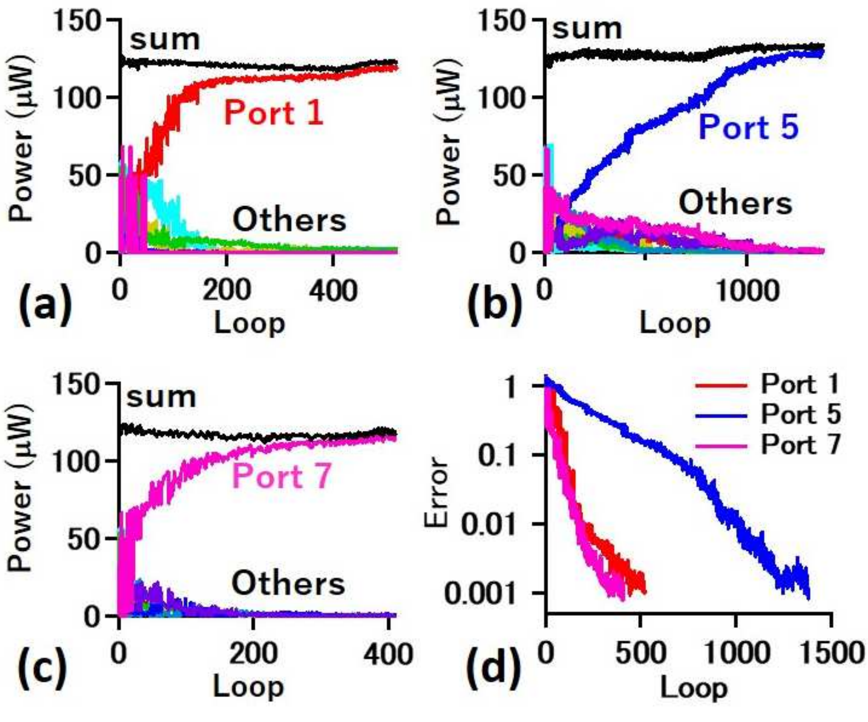

Fig. 2: Measured optical powers at all output ports and the total power evolved with the optimization loop for different target ports: (a) port 1, (b) port 5, and (c) port 7. (d) MSE error against the optimization loop.

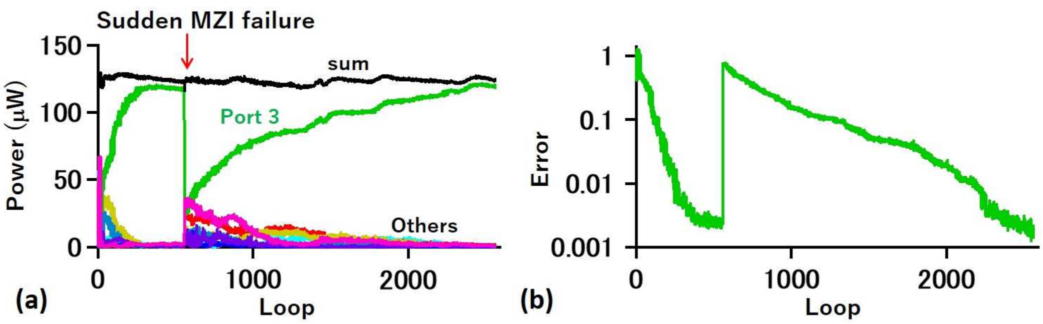

Fig. 3: (a) Measured optical powers of all ports for reconfiguration to the target port 3 and a failure intrigued recovery. The "o" MZI is shown in Fig. 1(a). (b) Corresponding MSE error during the progress of (a).

Conclusions

We experimentally demonstrated automatic reconfiguration and failure recovery for silicon photonic circuits by bacterial foraging algorithm. This method can be implemented in digital processors to realize error-tolerant self-reconfiguration and self-failure-recovery for programmable silicon photonic circuits.

Acknowledgements

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