

Large-scale reconfigurable continuously-coupled integrated optical circuits for photonic quantum information processing

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Abstract: Quantum photonic platforms are emerging as the most promising to prove a computational advantage. Here we present a novel reconfigurable integrated interferometer for large scale implementation of Boson Sampling based on the continuous-coupling of waveguides. © 2021 The Author(s)

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1. Introduction

One of the advantages of photonic platforms in quantum information processing is the possibility to decompose any unitary transformation of single- and multi-photon states in a sequence of elementary linear optical units. In literature, two universal and equivalent schemes have been proposed to realize any transformation by mean of beam splitters and phase shifters [1, 2]. They have found straightforward experimental implementations in integrated photonic devices, which offer in addition the ability to reconfigure the circuit by exploiting tunable phase shifters. The limitations of the discrete decomposition regard the high sensitivity to fabrication imperfections and photon losses. The main reason of such unfavorable behaviors, that become crucial for the realizations of large-scale instances of photonic circuits, is the scaling of the optical elements and of the circuit depth required to realize m -port interferometers. Nowadays, photonic Boson Sampling and, more recently Gaussian Boson Sampling, require complex optical circuits and high degree of reconfigurability to prove a quantum computational advantage [3, 4]. This work aims at finding and investigating alternative decompositions that mitigate the current limitations of integrated devices. A possible solution is given by the continuous coupling model of radiation among waveguides arranged in 1D or 2D lattices. In this approach the geometry of the lattice determines the Hamiltonian of the system. The unitary transformation that represents the operation of the optical circuit derives from the integration of the Hamiltonian over the interaction length, i.e. the circuit's portion in which the waveguides exchange the radiation. This architecture results in higher compactness, less circuit depth and photon losses compared to the previous mentioned decompositions [5]. In the following we illustrate the performances of such devices for implementing experimentally a large number of random extracted unitary transformations and for performing Boson Sampling. Then, we discuss a possible procedure to obtain a full programmable photonic processors based on the technology presented in this work.

2. Results

In Fig 1 we report the integrated device that is made by 32 continuously-coupled single-mode waveguides arranged in a 3D layout that display in the cross section a 8×4 triangular lattice. The chip has been fabricated thanks to the 3D capabilities of the femto-second laser writing technique [6]. The waveguide positions are randomly modulated from the lattice's position along the propagation coordinate z . These modulations are necessary to introduce randomness in the resulting the circuit transformation, which make the device suitable for a Boson Sampling experiment. The chip is equipped with 16 resistive heaters that have been patterned with the same laser-writing technology on the gold film placed on the top surface of the device. The dissipated power induced by currents applied to the resistors produces thermal gradients in the substrate and thus locally changes the refractive index of the waveguides. This allows to change dynamically the transformation U implemented in the integrated device. We have tested the reconfigurability of the system by comparing the sub-matrix reconstructed by injecting

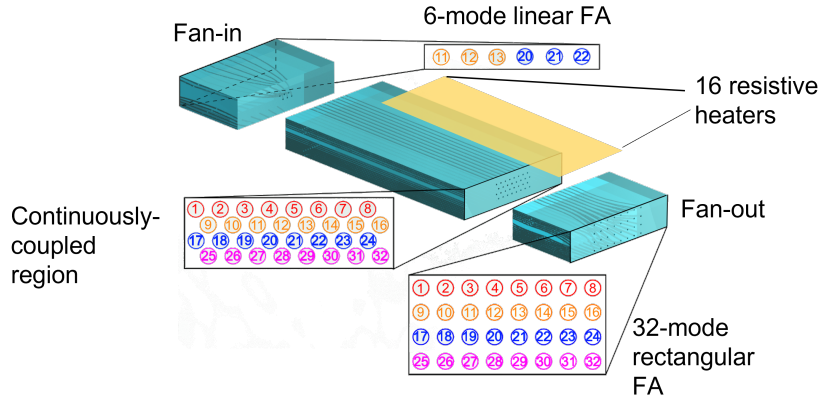


Fig. 1. Reconfigurable continuously-coupled optical circuits. 32-mode circuit based on the coupling among waveguides arranged in a 3D layout. The lattice displays a 2D triangular lattice cross section in the transverse plane. In the scheme are highlighted the interaction region and the fan-in and fan-out to connect the chip with external linear and rectangular fiber arrays (FA) respectively. The 16 heaters written in the gold film placed on the top surface of the glass sample allow to change the unitary transformation implemented in the optical circuit.

single and pairs of photons in three inputs of the device with likewise random sub-matrix extracted from the Haar-distribution. In this regard, the first investigation was focused on the distributions of phases and moduli of matrix elements. The second step was to quantify somehow the number of unitary transformations covered by extracting uniformly the electrical power dissipated in the heaters. To this aim we have calculated the distribution of the similarities between the squared moduli of matrix columns resulting from different set of dissipated powers in the heaters and compared with the same quantity estimated from Haar random matrices. The values of the similarities and the overlaps with the theoretical histograms of random unitary transformations are very encouraging for the task we are looking for. The further investigation carried out with the device was the observation of quantum interference due to multi-photon indistinguishability in 3- and 4-photon Boson Sampling. We have successfully collected samples for different unitary transformations and validated the data against mock-up hypotheses, such as the uniform and distinguishable particles samplers. The last issue regarding the use of such technology for quantum information processing regards the ability to have a full control over the transformation implemented in the optical circuit. Indeed it is not straightforward to individuate the relation between the dissipated powers and the matrix elements of the transformation. To this aim we are developing and testing optimization algorithms and in particular neural networks to find a reliable routine that helps in programming the circuit for realizing a given unitary operation.

Our findings prove that the proposed highly-reconfigurable layout could represent an invaluable building block for large-scale photonic experiments, and, in perspective, a viable direction for computing with photonic processors

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