# Microring resonator based single qubit unitary for photonic quantum information processing

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## Abstract

Here we propose an architecture based on microring resonators that implement arbitrary single qubit unitary transforms (i.e., gates) useful in path encoded photonic quantum information processing. The proposed device offers improved scalability in terms of size and operation when compared to the Mach-Zehnder Interferometer approach.

The use of photons as carriers of quantum information offers several advantages over matter based approaches: 1) photons are robust against noise (i.e., loss and decoherence) because of their weak coupling to the external environment [1]; 2) measurement is easy and has been demonstrated to occur at high efficiencies >95% [2]; 3) photons will be used in future quantum networks and communications; and 4) integrated photonics offers the ability to manufacture large-scale photonic systems [3]. In addition, the theoretical work by Knill, Laflamme and Milburn in 2001 (i.e., the KLM protocol) shows that the exponential speed ups of universal quantum computation are possible using only single photon sources and detectors, and linear optical components [4]. These details motivate research in the field of integrated quantum photonics (IQP) — which hopes to implement practical quantum technologies in areas such as computing, by harnessing the advantages provided by existing integrated photonic platforms [1].

In the last two decades, there have been several successful experiments demonstrating proof of concept systems for scalable photonic quantum computers built on an integrated photonics platform [5]–[7]. The approaches in the literature have focused on the using Mach-Zehnder Interferometers (MZIs), constructed from two directional couplers, which form 50:50 beam splitters, and an actively tuneable phase modulator. These MZIs are connected together to create photonic integrated circuits (PICs) that are capable of manipulating 'dual-rail' or 'path encoded' photonic qubits, where the computational basis states $|0\rangle$ and $|1\rangle$ of a qubit are represented by presence or absence of a single photon in semiconductor waveguides. The combination of two phase modulators, one before and one after the MZI, allow for the implementation of an arbitrary unitary transform on an inputted quantum state. The utilization of silicon photonics, means that these phase modulators are electrically controllable, forming programmable PICs that allow for the sequence of quantum transformations to be easily reconfigured.

However, there are issues when it comes the scalability of these systems. Most prominently, the traditional MZI systems are large: for example the device used by Harris et al. in 2017 had a approximate density of unitary transforms of $\backsim (100\mu m)^2$, based on the included dimensions [7]. In order to achieve universal fault tolerant photonic quantum information processing (QIP), thousands of ancilla qubits and likely millions of unitary transforms (i.e., quantum gates) as well as extensive post-selection and feed-forward operation will be needed. All of this requires space, a limited resource on integrated photonic chips, making any increase in the density of on-chip quantum operations helpful.

For this and many other reasons, we are proposing an architecture for photonic QIP that is based on optical microring resonators (MRRs) that implement arbitrary unitary transformations on inputted path encoded qubits. In terms of size, this architecture is much more compact than the familiar directional couplers used in the traditional MZI-based systems. The basic building block of both proposed devices, is a dually-stacked MRR configuration, shown in Figure 1a), that allows for the forward propagation of photons from input (i.e., source) to output (i.e., detection). As described by Hach et at. [8], a single MRR exhibits the Hong-ou-Mandel (HOM) effect, a quintessential optical quantum interference effect that proves that an MRR can operate as a 50:50 optical beam splitter. Using a scattering-transfer matrix formalism, we have shown that the dually-stacked ring configuration exhibit a very robust HOM effect, illustrated by the wide dip at $\theta = 0$ in Figure 1b). By operating both rings either on resonance (i.e., $\theta = 0$) or at a detuning of $\theta = \pi/3$, the stacked rings operate as a 50/50 beam splitter.

The proposed configuration seen in Figure 1d), is constructed by using both the stacked MRRs as 50:50 beamsplitters and the all-pass MRRs as phase shifters. This device is able to apply an arbitrary unitary transformation on an inputted quantum state by changing the detuning of the all-pass ring resonators; with $\phi$ controlling the probability amplitude of each basis state (i.e., $\alpha$ and $\beta$, see Figure 1c ) and $\varphi$ controlling the relative phase between each basis state (i.e., waveguide).

To conclude, we will discuss the specific improvements in the scalablity offered by the MRR architecture. As described initially, using MRRs provide a very large improvement in the density of on-chip unitaries. The footprint of the proposed architecture is $1100\mu m^2$, allowing for more computational power to be placed in the same area as compared to the MZI system. The stacked MRR configuration also benefits from the inherent scalability of a larger number of degrees of freedom (a

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total of four: $\theta_1$, $\theta_2$, $\kappa$ and $\gamma$) for controlling the operation of the single qubit unitary. The optical path length, $\theta$, is easily tuned to maintain 50:50 beam splitting, allowing for more robust control during operation compared to the traditional directional couplers used in the MZIs systems which doesn't have that functionality. MRRs also allow for the coupling coefficient between the rings and waveguides, i.e., $\tau, \kappa$ to be actively tuned, as discussed by Hach et al. [8], by using the design proposed by Chen, Sherwood-Droz, and Lipson [9].

In addition, the use of this proposed devices is not limited to use in gate based photonic QIP; devices that use a specific underlying network of interferometers, as the proposed architectures do, are able to perform quantum simulations, boson sampling and implement machine learning algorithms [1], [2], [10]. Therefore, this proposed device could be useful in applications of photonics outside of QIP, whenever arbitrary $N \times N$ unitary transforms are used to manipulate information encoded using optics.

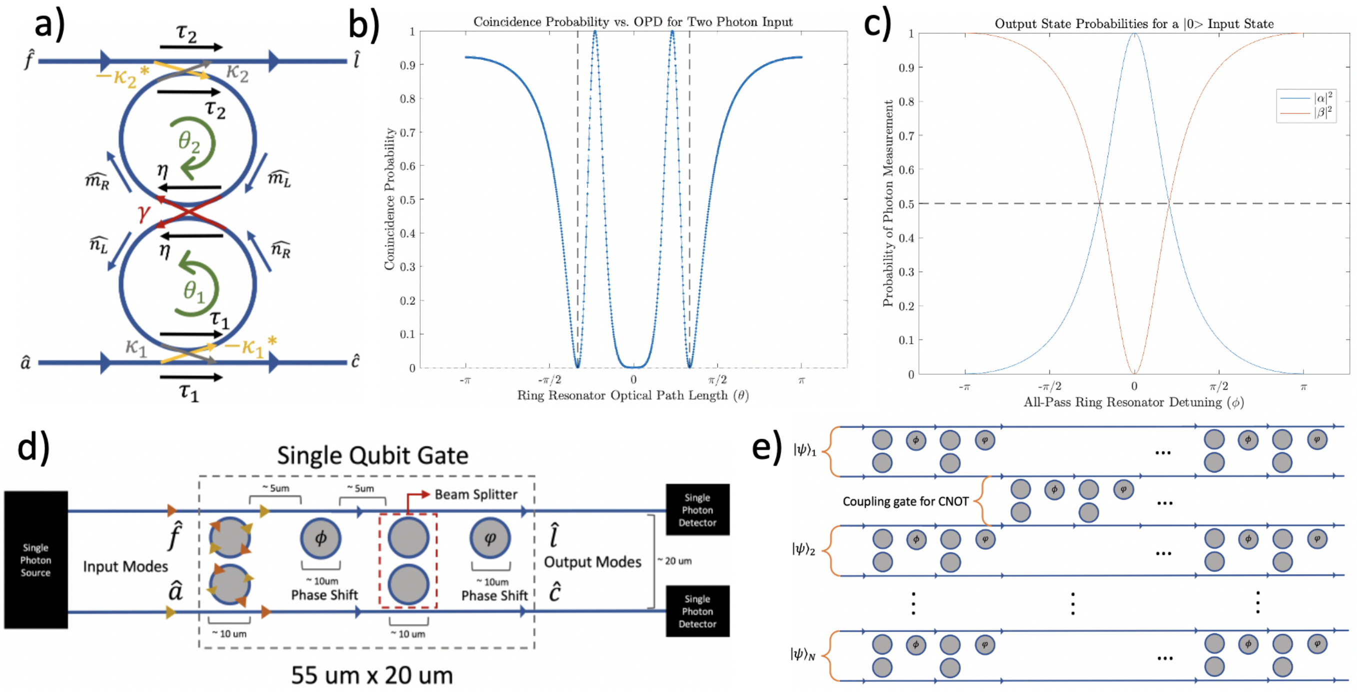

Fig. 1. a) Schematic of the stacked ring configuration, displaying the relevant modes and transition coefficients. b) Coincidence probability as a function of ring detuning from the output of the stacked MRR. c) Outputted probability amplitudes of the MRR-based unitary transform. d) Photonic circuit schematic of the proposed MRR-based single qubit gate/unitary. e) Application of the proposed MRR device to create a larger, universal linear photonic circuit that can implement multi-qubit operations such as the CNOT or quantum transport simulations [10]. Design based on and inspired by Clements et al. [11], Carolan et al. [6] and Harris et al. [7].

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