Linear optical quantum information processing via stacked micro-ring resonators

*Matteo P. Pennacchietti, †Alex N. Tait, *Bhavin J. Shastri
*Department of Physics, Engineering Physics and Astronomy, Queen's University
99 University Ave, Kingston, ON K7L 3N6, Canada
† Applied Physics Division, National Institute of Standards and Technology (NIST),
325 Broadway St, Boulder, CO 80305 United States
m.pennacchietti@queensu.ca

Abstract: Here we propose an architecture for path encoded photonic quantum information processing based on micro-ring resonators. This scheme increases on-chip component density and more naturally incorporates error mitigation, when compared to the Mach-Zehnder Interferometer approach.

1. Introduction

The use of photonic integrated circuits (PICs) – monolithically integrated single chip systems built using semiconductor waveguides and optoelectronics – have had important impacts on classical information systems [1]. Over the past decade, several experiments on PIC platforms, such as Silicon-on-Insulator (SOI), have demonstrated N-mode by M-mode unitary transformations on path encoded qubits - a first step towards linear optical quantum computing (LOQC) protocols [2]. These systems utilize mesh's of Mach-Zehnder Interferometers (MZIs) that each act as the fundamental component of a linear optical circuit – a reconfigurable beam splitter (RBS) [2].

2. Micro-ring resonators for QIP

If fault-tolerant photonic quantum information processing is to be achieved, then component density, propagation losses, fabrication variation and integrability must all be improved. Our research has therefore focused on improving the scalability of these linear optical systems by using integrated optical micro-ring resonators (MRRs) as the fundamental PIC components, instead of the MZIs. We have done a comprehensive analysis showing the viability of using only MRRs for implementing unitary transformations on path-encoded photonic qubits for use in LOQC schemes. There have been previous investigations into the use of MRRs for quantum optical applications, namely as photon sources [3], but also for linear optical applications [4, 5]. The novelty of this research is twofold: 1) we propose an alternative architecture using of stacked ring resonators (STARRs) which improves scalability compared to the single double-bus MRR discussed in the literature [4, 5]; and 2) our work provides a detailed analysis of the practicalities of such a system and compare it directly to the existing MZI approach.

We model the STARR system by employing a lumped element, linear optical transition approach based in the continuous-wave limit that incorporates photon loss due to propagation scattering via a fictitious beam splitter. Using this model, we find that when both MRRs are tuned to their resonant frequency, there is strong Hong-Ou-Mandel (HOM) interference in a STARR, up to high loss rates over 10% (see Figure 1b). When one ring is on resonance and the other is detuned, both 50:50 beam splitting and variable optical phase delay can be imparted on two independent spatial modes (see Figure 1d). Excitingly, this exact effect has very recently been demonstrated experimentally [6]. By placing two STARRs in cascade, we find that reprogrammable unitary transforms can be implemented. By controlling the detunings of both STARRs, the splitting ratio and the effective path length between each mode can be adjusted, in an analogous manner to the functionality present in MZI systems. This allows for the STARR system to be inserted into existing architectures that enable multi-mode unitary transforms that have applications in both quantum and classical information processing.

We have found a number of improvements in the overall scalability of future linear programmable photonic circuits that employ STARR-based transformations. Most notable is around a 5x increase in the component density for Silicon-on-Insulator (SOI) chips arising from the fact that a single STARR contains the functionality of both a single integrated directional coupler and an optical phase delay element. In addition, MRR devices that employ interferometric ring-waveguide coupling [7] allow for more precise operation when working with realistic devices that suffer from fabrication variation. From our analysis, we also show that both the MZI system and STARR system in Figure 1c) behave the same when in the presence of loss, i.e., in both cases the quantum state fidelity at the output of a circuit behave the same as a function of loss.

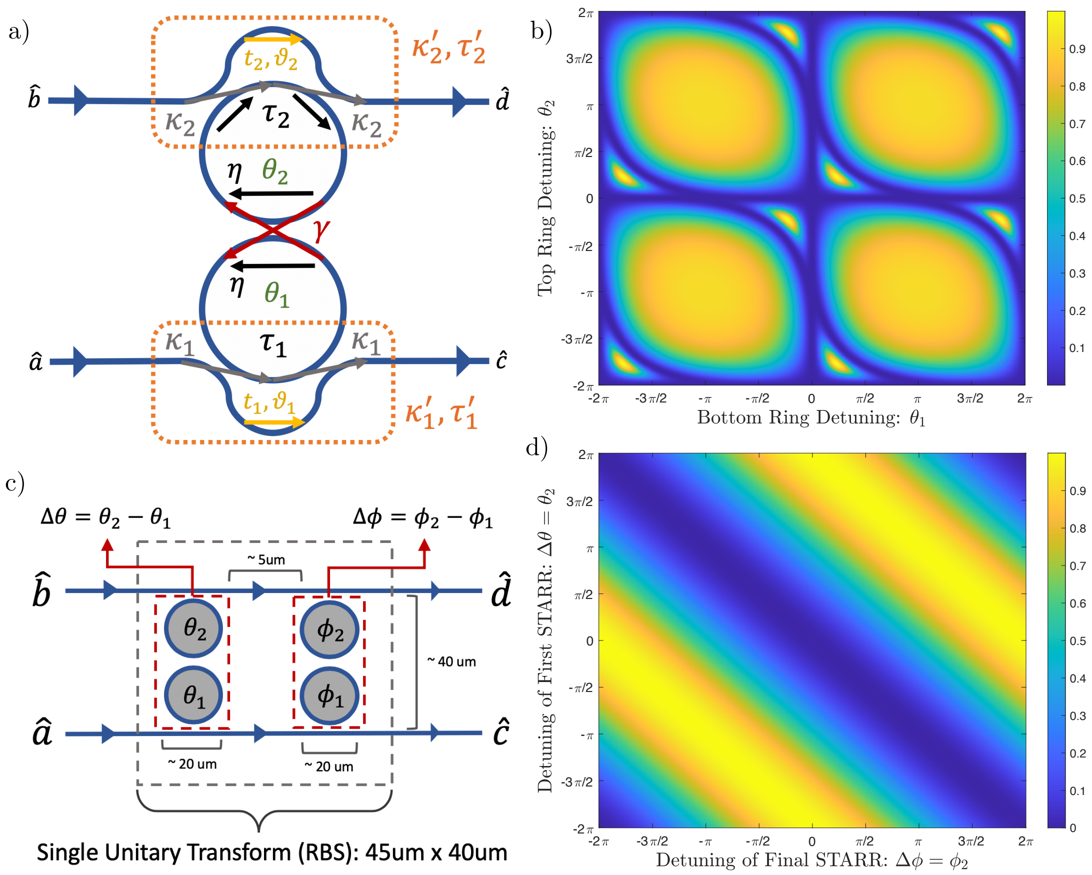


Fig. 1. a)Stacked MRR (STARR) system with interferometric coupling to the top and bottom bus waveguide as described by Ref. [7]. b) Coincidence probability for modes d and c as a function of the detuning of the top and bottom rings from resonance. c) Schematic of two cascaded STARRs which allows for unitary transformations on input modes a and b. d) Probability of measuring the output of figure c) as $|0\rangle_d |1\rangle_c$ if the input state is $|0\rangle_b |1\rangle_a$. It is clear that the transition amplitudes follow a sinusoidal relationship with the detunings ϕ_2 and θ_2.

References

1. W. Bogaerts, P. de Heyn, T. van Vaerenbergh, K. de Vos, S. Kumar Selvaraja, T. Claes, P. Dumon, P. Bienstman, D. van Thourhout, and R. Baets, "Silicon microring resonators," Laser Photonics Rev. **6**, 47–73 (2012).
2. N. C. Harris, J. Carolan, D. Bunandar, M. Prabhu, M. Hochberg, T. Baehr-Jones, M. L. Fanto, A. M. Smith, C. C. Tison, P. M. Alsing, and D. Englund, "Linear programmable nanophotonic processors," Optica **5**, 1623 (2018).
3. E. Engin, D. Bonneau, C. M. Natarajan, A. S. Clark, M. G. Tanner, R. H. Hadfield, S. N. Dorenbos, V. Zwiller, K. Ohira, N. Suzuki, H. Yoshida, N. Iizuka, M. Ezaki, J. L. O'Brien, and M. G. Thompson, "Photon pair generation in a silicon micro-ring resonator with reverse bias enhancement," Opt. Express **21**, 27826 (2013).
4. R. E. Scott, P. M. Alsing, A. M. Smith, M. L. Fanto, C. C. Tison, J. Schneeloch, and E. E. Hach, "Scalable controlled-not gate for linear optical quantum computing using microring resonators," Phys. Rev. A **100** (2019).
5. E. E. Hach, S. F. Preble, A. W. Elshaari, P. M. Alsing, and M. L. Fanto, "Scalable Hong-Ou-Mandel manifolds in quantum-optical ring resonators," Phys. Rev. A **89**, 043805 (2014).
6. J. Serafini, D. Spiecker, J. Steidle, M. Fanto, E. Hach, and S. Preble, "Two photon interference via coupled ring resonators on a silicon photonic chip," in *Conference on Lasers and Electro-Optics,* (Optical Society of America, 2020), p. FTu4C.7.
7. L. Chen, N. Sherwood-Droz, and M. Lipson, "Compact bandwidth-tunable microring resonators," Opt. Lett. **32**, 3361 (2007).

Linear optical quantum information processing via stacked micro-ring resonators

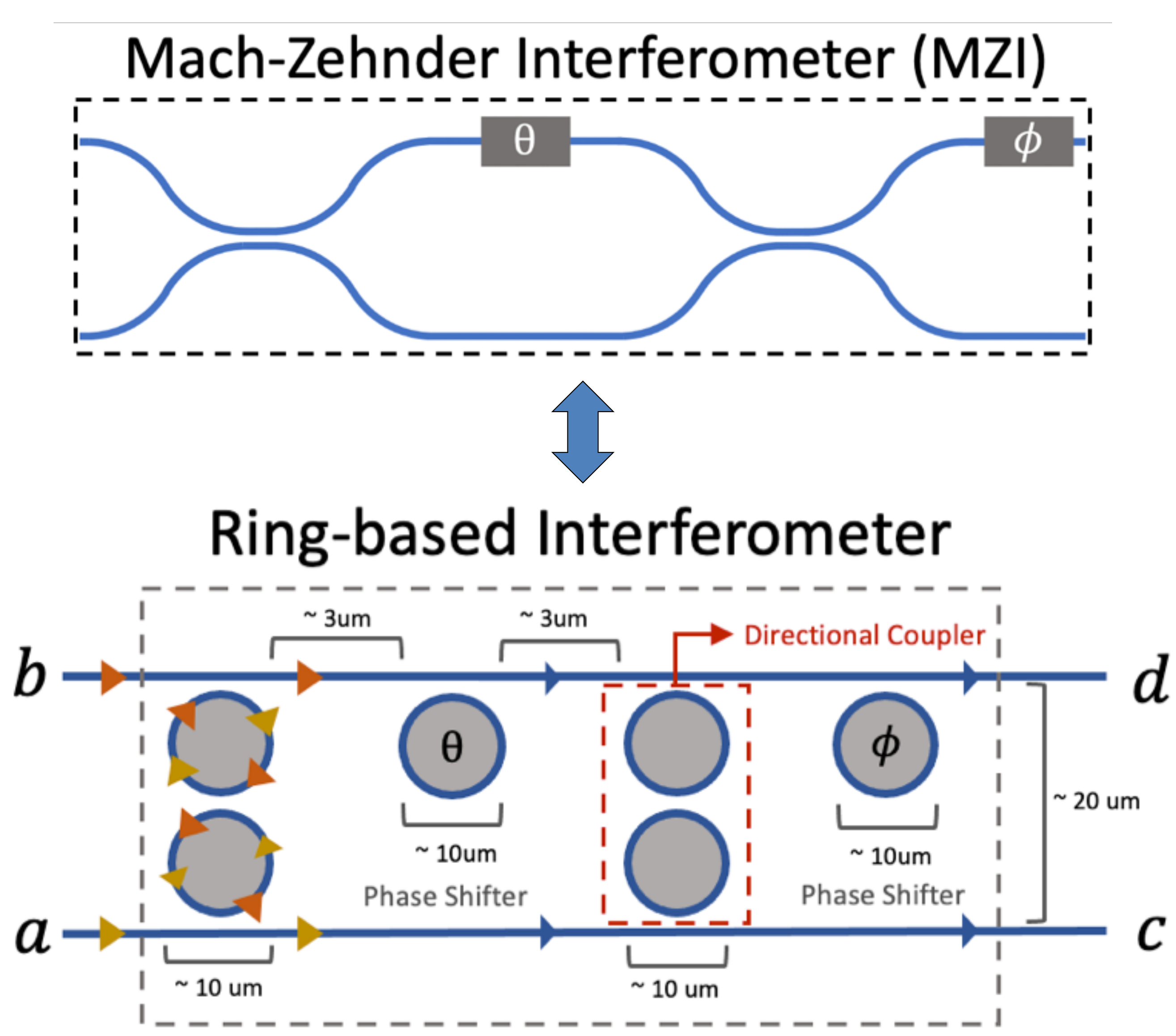
Matteo P. Pennacchietti[1] , Alex N. Tait[2], Bhavin J. Shastri[1]

1. Dept. of Physics, Eng. Physics and Astronomy, Queen's University, Kingston, ON, Canada
2. Applied Physics Division, NIST, Boulder, CO, USA

Introduction and Motivation

Optical approaches to quantum information processing have become increasingly popular in recent decades, spurred in large part by the development of high-quality photonic integrated circuits (PICs). These devices enable many optical and electronic components to be fabricated on a silicon wafer, delivering the large-scale integration necessary to scale up to the large number of physical qubits. Manipulations of path encoded, or dual-rail photonic qubits has been performed on PICs using networks of Mach-Zehnder Interferometers (MZIs) constructed from directional couplers and electrically controllable phase-delay elements [Harris 2017, Carolan 2015]. Here, single-photon undergo a unitary transformation based on the phase delays ϑ and ϕ. The on-chip footprint of individual MZIs in current Silicon-on-Insulator (SOI) devices is around 100um x 100um or larger, which enables 88 interferometers to be placed on a 4.9mm x 2.4 mm chip [Harris 2017].

It is likely more compact components will be necessary to increasing the number of photonic qubits available on chip [Harris 2018]. In contrast to the current generation of MZIs, micro-ring resonators (MRRs) have been fabricated on SOI to be compact (radii of 5-10um) and have low loss (1-3 dB/cm) [Xiao 2007]. This, as well as previous literature [Hach ,Scott 2019], motivated our investigation into using micro-ring resonators (MRRs) as the primary optical component for manipulating path-encoded qubits on-chip. To facilitate the feed-forward propagation of photons, we explored using two stacked MRRs which we call STARRs (also known as CROWS), as tunable directional couplers. Single all-pass MRRs coupled to the top waveguide act as a tunable phase delay elements, like the traditional linear designed employed in MZI-based systems [Harris 2014]. It is essentially emulating the interferometric structure of an MZI using MRRs. For this reason, we call this system the Ring Interferometer Single Qubit (RISQ) gate.



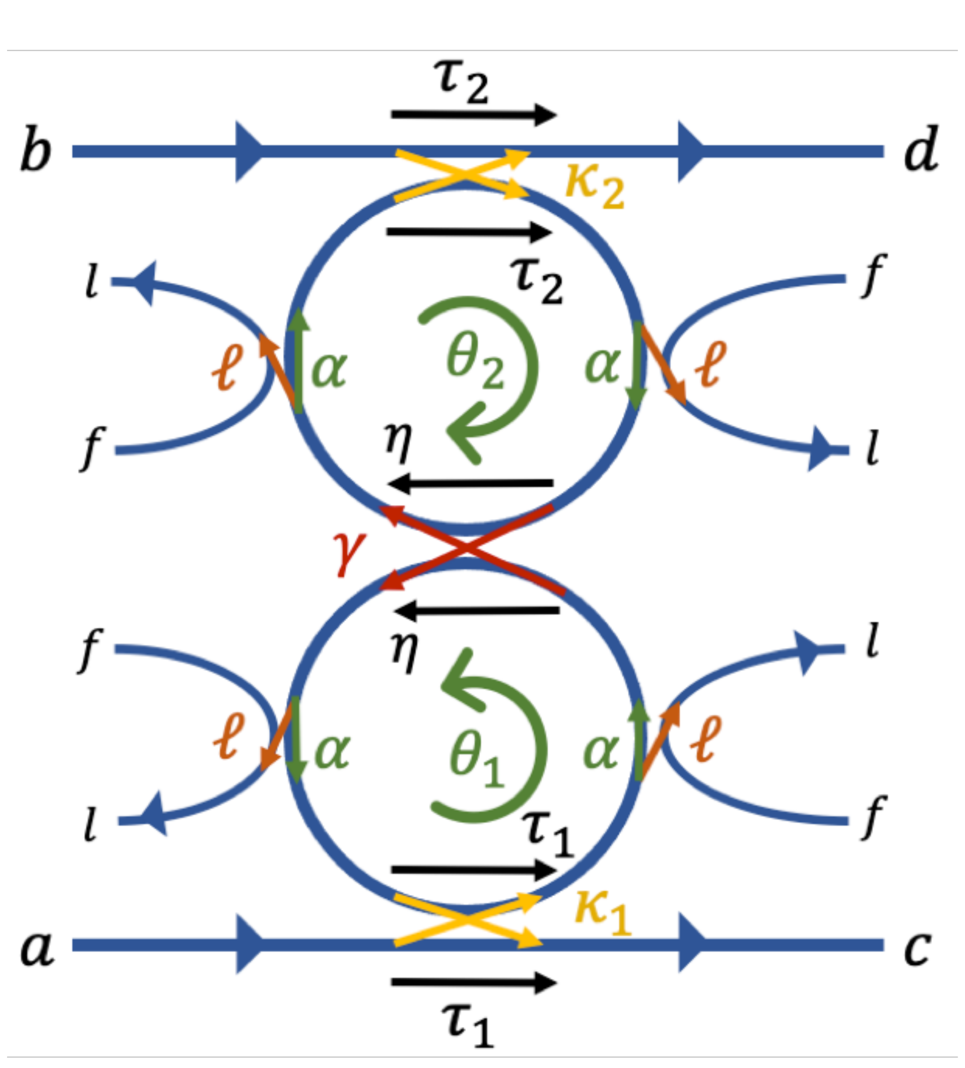
Top: Schematic of a traditional MZI single qubit gate. Bottom: Proposed RISQ system which we have investigated as an alternative to the MZI and can implement arbitrary, re-programmable unitary transformations on path encoded qubits by changing the detuning's of the different rings.

Methods and Analysis

To model the rings, we used a simple scattering matrix approach. The transition coefficients between the different portions of the system are based on the effective power coupling ratios of standard direction couplers, implying $|\tau|^2 + |\kappa|^2 = 1, |\gamma|^2 + |\eta|^2 = 1$. Here we have taken that τ to be real and $\kappa = i\sqrt{1-\tau^2}$. As photons travel through the arms of the ring, they pick up a factor of $\exp(-i\theta)$, where θ is the optical path length of a given ring segment which can be altered using thermo-optic tuning for example. Loss was incorporated into the model using the common fictitious beam splitter approach [Mower 2015, Alsing 2017]. Here ℓ represents the loss rate of photons out of the waveguide and is related to the power spectrum of the MRR.

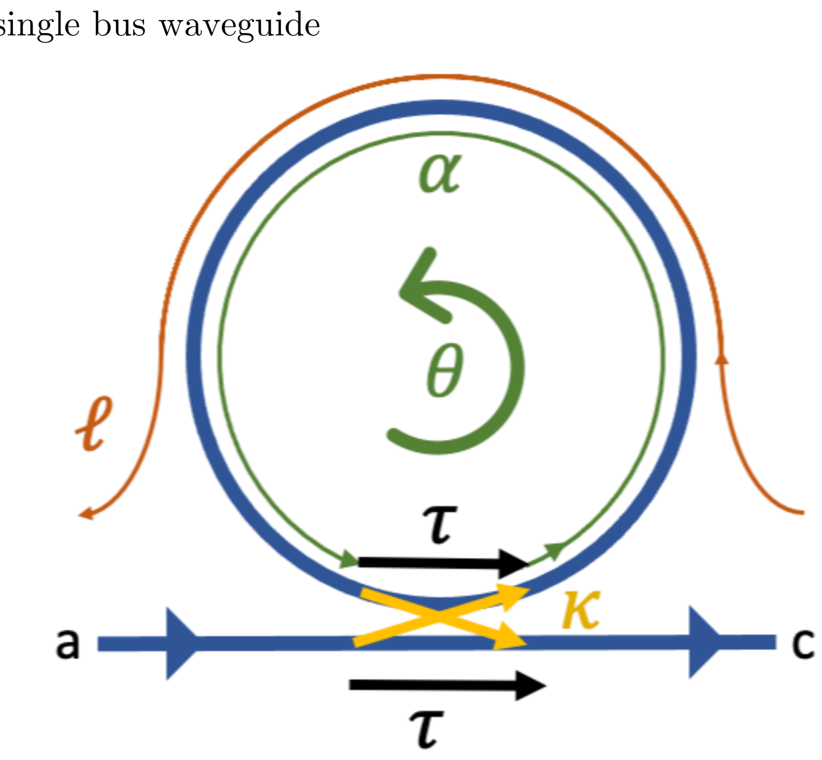
When the stacked MRRs are both set to be on resonance with $\tau^2 = \gamma^2 = 1/2$, the system implements an essentially identical scattering matrix to that of a directional coupler. The all-pass rings apply an effective phase delay to the waveguide it is coupled to based on the coupling and the path length of the ring (ϕ *or* φ). The overall scattering matrix takes the form of an SU(2) rotation like that of an MZI [Harris 2017]:

$$U = \frac{1}{2}\begin{bmatrix}1 & 0\\ 0 & e^{i\varphi'}\end{bmatrix}\begin{bmatrix}1 & -i\\ -i & 1\end{bmatrix}\begin{bmatrix}1 & 0\\ 0 & e^{i\phi'}\end{bmatrix}\begin{bmatrix}1 & -i\\ -i & 1\end{bmatrix} = -ie^{i\phi'/2}\begin{bmatrix}\sin(\phi'/2) & \cos(\phi'/2)\\ e^{i\varphi'/2}\cos(\phi'/2) & -e^{i\phi'/2}\sin(\phi'/2)\end{bmatrix}$$

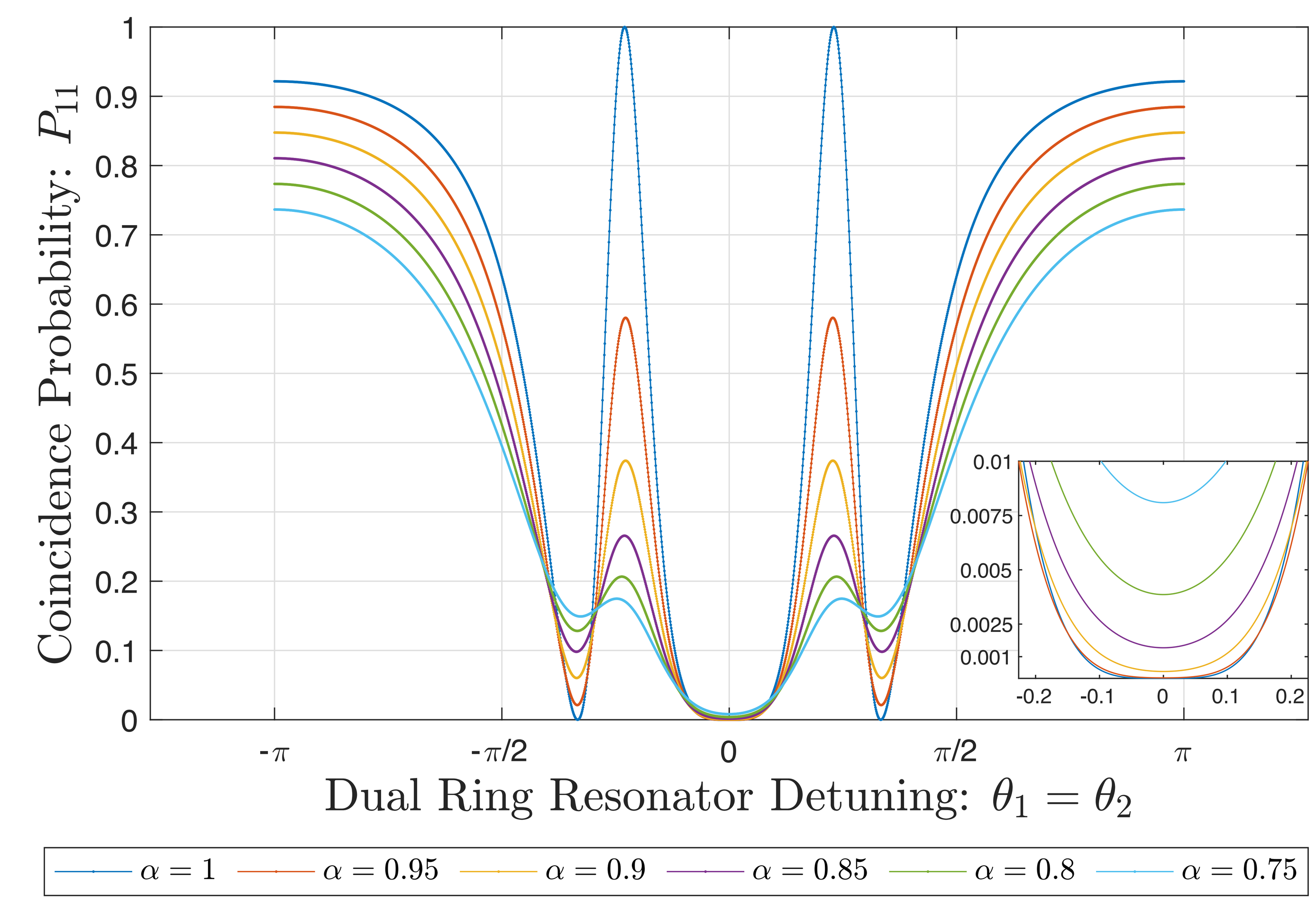


Left: Schematic of a lossy, stacked MRR coupled to two bus waveguides, including the fictitious beam splitters and loss modes which effectively couple to the arms of each MRR.

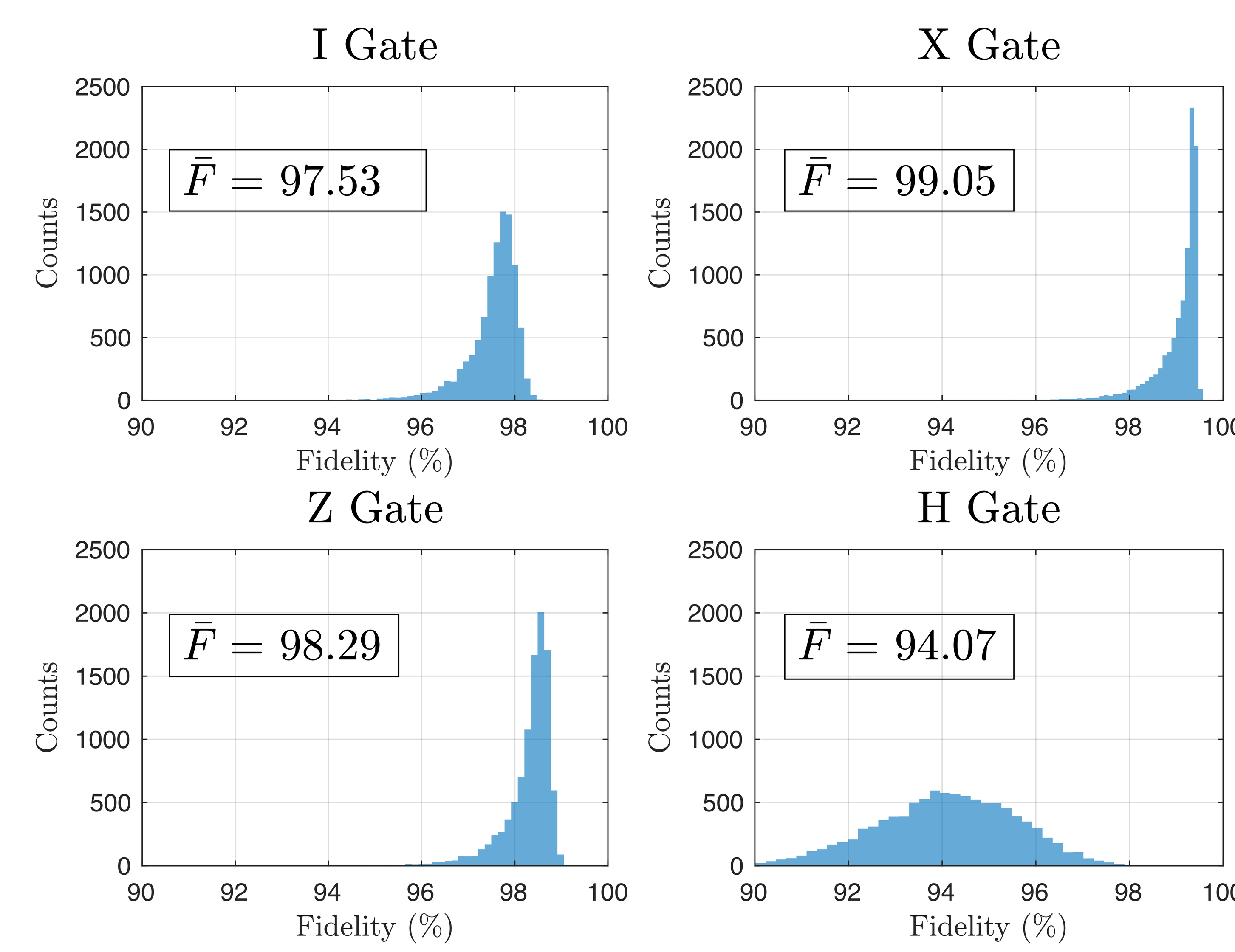
Bottom: Schematic of an all-pass MRR coupled to a single bus waveguide



Results



Plot of the probability of simultaneously measuring a photon in both waveguides after inputting a single photon into each waveguide, for various loss rates. Here we have chosen $\tau^2 = \gamma^2 = 1/2$. The plot indicates the presence of a Hong-Ou-Mandel (HOM) effect (i.e., no simultaneous photon detections) when both rings are tuned at resonance ($\theta_1 = \theta_2 = 0$). The HOM effect is present in stacked MRRs even when loss rates are relatively high. This effect has been observed experimentally [Serafini 2020].



Right: Results of a Monte Carlo simulation of several different single qubit gates using realistic loss and coupling variation values. A similar analysis of realistic MZI systems was performed by Mower et al. in 2015. 10000 coupling (τ) values and loss (ℓ) values were sampled from a Gaussian distribution with mean (std.) of 1/2 (0.043) [Mower 2015] and 0.0027 (0.0004) [Xiao 2007], respectively. The steep cut-off of the histogram on the right side of the X plot is caused by photon loss dominating the maximum fidelity of that gate. However, the Gaussian-like shape of the I,Z and especially H histograms reflects the fact that fabrication errors dominate the reduction in fidelity. This difference results from the fact that the X gate rings are in a stable point where the transformation is more sensitive to loss than to changes in coupling coefficient. The H gate is implemented at a detunings that correspond to less stable points in the system.

Conclusion

- The RISQ system can be inserted into existing architectures for larger unitary transformations, including two qubit gates [Carolan 2015, Harris 2018].
- MRRs offer a potential increase in component density, ranging from a factor of 2-10 compared to MZIs. Exact improvement depends on how one designs the 50/50 ring-waveguide couplers.
- Because the stacked MRRs can themselves be tuned, fabrication variation errors away from 50/50 splitting may be able to be locally compensated, without the need for additional components.
- In addition, MRRs offer interesting flexibility in terms of types of coupling. Example, interferometric type ring-waveguide coupling [Chen 2007].
- Reducing the total number of rings would be a simple approach to improving performance.
- MRRs may suffer more acutely from photon loss than MZIs.

New research questions:

- What would a physical fabrication design look like for this system?
- Can the fidelity be improved by tuning the stacked rings? Can it outperform an equivalent MZI system?
- How would the system perform implementing a two-qubit gate (CNOT)?
- Are there other configurations of MRRs that can implement arbitrary unitary transformations?

References and Acknowledgments

Carolan et al. Science 2015, 349, 6249.
Harris et al. Nat. Phot. 2017, 11.
Harris et al. Optica 2018 5, 12.
Xiao et al. Opt. Exp. 2007 15, 22.
Chen et al. Opt. Exp. 2007 32, 22.
Mower et al. Phys. Rev. A 2015 92, 032322.
Hach et al. Phys. Rev. A. 2014 89, 043805
Alsing et al. Phys. Rev. A. 2017 95, 053828.
Scott et al. Phys. Rev. A. 2019 100, 022322
Serafini et al. Proc. CLEO. 2020 FTu4C.7.

The authors would like acknowledge fruitful conversations with Nir Rotenberg and Marc Dignam.