Quantum Logic Gates on Time-bin Encoded Photonic Qubits

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For the ENPH 455 Engineering Thesis I am working under the supervision of Prof. Nir Rotenberg and Jacob Ewaniuk to design a realistic computational model describing how to perform linear unitary transformations relevant to quantum logic gates on time-bin encoded photonic qubits. Photonic quits are an excellent candidate for quantum information processing as they have shown quantum advantage. Currently, there are different systems that perform linear unitary transformations using Mach-Zehnder interferometers. The system considered relevant for this project is the Clement's configuration which generates an N x N mesh of interferometers [1]. This process can be altered by including time-bin encoding which reduces the number of interferometers to three and only needs one input and one output node. This architecture can be compared to the Clement's configuration, where N input and output nodes are needed as well as N interferometers. Time-in encoding allows for any size mesh to be produced and reduces the physical space of the set-up [2].

The main goal of this project is to make a computational model which should be able to perform the necessary transformations on quantum logic gates utilizing the time-bin architecture while also taking into consideration different circuit imperfections. The system will consist of two nested loops, at either ends of the loops there will be on/off switches and in the center where the loops overlap there will be an interferometer. The correct size of the loops will need to be chosen to ensure the photons interact at the correct times to when they are in the circuit [3]. There have several past works that take advantage of time-bin encoding mixed with other techniques. A popular technique to use is polarization separation, although this will likely not be the avenue followed, many techniques used in these works can be adapted for this project [4].

This final product should be able to perform a CNOT gate to demonstrate its relevance to quantum information [5]. Another major component of the project is the mathematical model which needs to describe multiphoton systems. For this, the Fock basis will be used as it is able to generate multiphoton matrices and is used in many quantum computational systems [6]. Computational power will be a major constraint, as there are several mathematical procedures that must be done which may take a long time on a personal computer. The design constraints are set by the finalized material choices, which include the interferometers and the fiber optic cable. The cable must be long enough to allow for time-bin encoding, and the interferometers should be able to perform the necessary phase shifts and transmission requirements for the circuit to function [3].

Bibliography

[1] W. R. Clements, P. C. Humphreys, B. J. Metcalf, W. S. Kolthammer and I. A. Walmsley, "Optimal design for universal multiport interferometers," *Optica 3,* pp. 1460-1465, 2016.

This article demonstrates a new arrangement of beam splitters and phase shifters that surpasses the previous design set by Reck et al. , which had been the base design used for multiport interferometers. The paper describes the physical way the interferometers work, and the mathematical descriptions of each. Beginning with a set unitary n x n matrix each interferometer applies phase changes. The paper provides the math needed to understand the unitary's final encoded state as well as the algorithm to decode the final unitary to determine the phase changes at each interferometer step. This is relevant so it can be understood how interferometers affect the system I am working with; the paper seems reliable.

[2] K. R. Motes, A. Gilchrist, J. P. Dowling and P. P. Rohde, "Scalable Boson Sampling with Time-Bin Encoding Using a Loop-Based Architecture," *Phys. Rev. Lett.,* vol. 113, no. 12, p. 120501, 2014.

This paper uses an architecture of two nested fiber loops to produce a time-bin encoded system. Photons enter the loops that are controlled by switches which allow for the construction of the desired interferometers. This design has only one interference point, which is found in the center of the two nested loops. This paper is relevant as it demonstrates a way of using time-bin encoding to generate the desired interferometer set up, which may influence my design. The paper seems credible and has been recently produced.

[3] P. P. Rohde, "A simple scheme for universal linear optics quantum computing with constant experimental complexity using fiber-loops," *Phys. Rev. A,* vol. 91, no. 1, p. 012306, 2015.

This paper further explains the double nested loop time-bin encoded architecture and its applications to quantum computing. It contrasts the nested loop architecture using polarization rotations and time-bin encoding, which is relevant as many past works have utilized polarization rotations. Some techniques from these works may be adaptable for this project, as they have been adaptable for time-bin encoding previously. The paper seems credible as the author of it has been cited in other relevant papers. It is also a recent publication.

[4] Y. He, X. Ding, Z.-E. Su, H.-L. Huang, J. Qin, C. Wang, S. Unsleber, C. Chen, H. Wang, Y.-M. He, X.-L. Wang, S.-J. Chen, C. Schneider, M. Kamp, L.-X. You, Z. Wang, S. Hofling, C.-Y. Lu and J.-W. Pan, "Time-Bin-Encoded Boson Sampling with a Single-Photon Device," *Phys. Rev. Lett,* vol. 118, no. 19, p. 190501, 2017.

This paper demonstrates the use of time-bin encoding for boson sampling using three and four single photons. The set up in the paper uses electro-optic modulators to generate polarization differences and the pulses are separated by polarization into 2 loops. The pulses are ejected from the loop and then measured. This paper is relevant as some techniques used are relevant to the project, it also describes how to measure the efficiency of a system using the time-bin architecture. The paper seems to be credible and was published recently.

[5] P. C. Humphreys, B. J. Metcalf, J. B. Spring, M. Moore, X.-M. Jin, M. Barbieri, W. S. Kolthammer and I. A. Walmsley, "Linear Optical Quantum Computing in a Single Spatial Mode," Optica Publishing Group, Berlin, 2014.

This paper outlines how different quantum logic gates (CPhase and CNOT specifically) can be made using a controlled polarization time-bin encoded system. They outline different considerations that must be taken when using the time-bin architecture, such as fiber length and the bandwidth of photon sources. Although the paper deals with polarization, it has aspects relevant to the project as the base architecture is the same. The paper seems credible as it is published in a credible journal, it is also still relevant today.

[6] S. Aaronson and A. Arkhipov, "The Computational Complexity of Linear Optics," in *Association for Computing Machinery*, New York, 2011.

This paper puts forth a model of quantum computation using non-interacting bosons. It describes how to perform a transformation from a single-photon unitary matrix to a multi-photon unitary matrix in the Fock basis. The Fock basis is used to describe these multi-photon matrices and will be used throughout the project. This paper explains the mathematics of building the Fock basis and is meant for people new to linear optics, so it will prove to be useful as the mathematical model is produced.