P7681 Final Project

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1 Summary of paper

P. J. Shadbolt, M. R. Verde, A. Peruzzo, A. Politi, A. Laing, M. Lobino, J. C. F. Matthews, M. Thompson, J. L. O'Brien, "Generating, manipulating and measuring entanglement and mixture with a reconfigurable photonic circuit," Nature Photonics 6, 45–49 (2012), arXiv:1108.3309

Shadbolt, et. al., demonstrate a photonic quantum circuit capable of arbitrary Qbit state preparation and canonical entanglement via a 2-Qbit CNOT gate. It is "reconfigurable" in the sense that it is capable of performing several different quantum operations, including pure/mixed state preparation and state/process tomography. This is made possible by using thermo-optically tuned phase shifters, such that each ϕ can be altered in the circuit:

$$\left[\hat{U}_f(\phi_5, \phi_6) \otimes \hat{U}_f(\phi_7, \phi_8)\right] \cdot \hat{U}_{CNOT} \cdot \left[\hat{U}_i(\phi_1, \phi_2) \otimes \hat{U}_i(\phi_3, \phi_4)\right]$$

where $\hat{U}_{CNOT} = |00\rangle\langle 00| + |01\rangle\langle 01| + |10\rangle\langle 11| + |11\rangle\langle 10|$, corresponding to the expected behavior of a 2-Qbit CNOT gate, and $\hat{U}_i(\phi_j, \phi_k) = e^{-i\phi_k\sigma_z/2}e^{-i\phi_j\sigma_y/2}$ and $\hat{U}_f = \hat{U}_i\dagger$ (the Hermitian conjugate). Each $\hat{U}(\phi)$ is essentially comprised of a "Hadamard-like" gate and a rotation $R_z(\phi)$ to prepare each Qbit.

The authors used a Mach-Zehnder interferometer and two phase shifters[1] to implement each $\hat{U}_{i,f}(\phi_j, \phi_k)$. In this setup, each ϕ_{1-8} can be controlled by adjusting the voltage applied to a heater. The paper does not specify how the heaters were implemented, but most photonic circuits use thin-film Ti resistive microheaters. A phase shifter can be constructed using, for example, a microring resonator coupled to two waveguides with $T \approx 1$.[2] The heater is used

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[1] This is sufficient for most, but not all, unitary operations in SU(2); it could be extended to encompass all of SU(2) by adding a third phase shifter.(1)

[2] Meaning that losses due to coupling or dispersion are negligible.

to tune the ring by slightly altering its diameter, which changes the effective optical path length.

The result is quantitatively evaluated in three ways: first, the MZI is used to measure the visibility of the Hong-Ou-Mandel dip, an effect that causes the rate of coincident photon measurement after passing through a 50/50 beam splitter to "dip" when two identical photons have perfect temporal overlap(2). The "HOM effect" is a quantum mechanical phenomenon; it occurs because the wavefunctions of each photon become indistinguishable. The visibility of the dip, measured as $V = (N_{classical} - N_{quantum})/N_{classical}$, was reported as 0.978, which the authors claim demonstrates that their circuit is of high quality (an optimal device would have $V = 1$). This is certainly an improvement over previous experiments yielding dips of 0.78(3) and 0.83(4), for example, although higher-visibility dips have been constructed by manipulating the polarization states of the input photons and using a highly asymmetric beam splitter(5).

Second, each of the four maximally-entangled Bell states is prepared by inputting a logical zero into each input, i.e., a single photon into each of two upper waveguides, by selectively altering each ϕ_{1-4}. Quantum-state tomography can then be performed by altering each ϕ_{5-8} (the output phase shifters) to characterize each state's density matrix, which can be used to verify entanglement(6). The authors also verify entanglement by calculating the Bell-CHSH sum, defined as $S = \left\langle \hat{A}_1 \hat{B}_1 \right\rangle + \left\langle \hat{A}_1 \hat{B}_2 \right\rangle + \left\langle \hat{A}_2 \hat{B}_1 \right\rangle - \left\langle \hat{A}_2 \hat{B}_2 \right\rangle$, where each $\left\langle \hat{A} \hat{B} \right\rangle$ pair is essentially the correlation between two separate measurement operators A(lice) and B(ob). Classically, this sum is bound by $-2 \leq S \leq 2$; experimental results found regions where the sum was outside that boundary, limited only by the quantum mechanical bound of $\pm 2\sqrt{2}$.

Finally, the fidelity of the CNOT component of the circuit is measured to be 0.990 ± 0.009, a very accurate result, and the fidelity of mixed state generation is measured to be 0.98 ± 0.002. This demonstrates a high-quality setup; the authors posit that the quality is mostly limited by birefringence and mode mismatch in the lasers used for single photon emission, and that it may be possible to configure the circuit better using repeated measurements and a genetic algorithm.

2 Accessibility

Parts of this paper were difficult to understand. SEM micrographs would have helped my understanding of how the MZIs and phase shifters are arranged to implement quantum gates. That being said, learning what the Bell inequality is and how it can be violated with quantum entanglement in class made it easier for me to understand what the Bell-CHSH measure means. I also would not have understood what any of the state preparation part of the circuit is doing without this class. Some parts of the paper (the HOM dip section in particular) were not covered in class; understandable given that the class was more theoretical and the HOM effect is only relevant to photonic experimental realizations.

References

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