AIP Conference Proceedings

Photonic quantum walks in a fiber based recursion loop

A. Schreiber, K. N. Cassemiro, V. Potoček, A. Gábris, I. Jex, and Ch. Silberhorn

Citation: AIP Conference Proceedings **1363**, 155 (2011); doi: 10.1063/1.3630170
View online: http://dx.doi.org/10.1063/1.3630170
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1363?ver=pdfcov
Published by the AIP Publishing

Photonic quantum walks in a fiber based recursion loop.

A. Schreiber*, K. N. Cassemiro*, V. Potoček†, A. Gábris†,**, I. Jex† and Ch. Silberhorn*,‡

*Max Planck Institute for the Science of Light, Günther-Scharowsky-str. 1 / Bau 24, 91058 Erlangen, Germany.
†Department of Physics, FNSPE, Czech Technical University in Prague, Břehová 7, 115 19 Praha, Czech Republic.
**Research Institute for Solid State Physics and Optics, Hungarian Academy of Sciences, H-1525 Budapest, P. O. Box 49, Hungary.
‡University of Paderborn, Applied Physics, Warburger Str. 100, 33098 Paderborn, Germany.

Abstract. We present a flexible and robust system for implementing one-dimensional coined quantum walks. A recursion loop in the optical network together with a translation of the spatial into the time domain ensures the possible increment of the step number without need of additional optical elements. An intrinsic phase stability assures a high degree of coherence and hence guarantees a good scalability of the system. We performed a quantum walk over 27 steps and analyzed the 54 output modes. Furthermore, we estimated that up to 100 steps can be realized with only minor changes in the used components.

Keywords: Quantum walk, Quantum simulations
PACS: 03.65.-w, 03.67.-a, 42.50.-p

INTRODUCTION

Quantum walks describe the coherent evolution of quantum particles in a discretized environment. In the case of coined quantum walks the spreading of the particle's wavefunction is determined by an internal quantum state (*coin state*). Superpositions in the coin state induce quantum interference, which leads to a quadratically faster spread compared to the evolution of a classical particle. Quantum walks constitute not only the basis for modelings of natural phenomena like the energy transfer in photosynthesis, but are an important resource for performing quantum algorithms. This emphasizes the need of an experimental implementation, that is not only flexible enough to simulate different physical scenarios but also scalable concerning the number of applicable modes and operations for computational applications. The first implementations of the quantum walk were realized in completely diverse ways: they were based on the manipulation of atoms [1] and ions [2] in traps, energy levels in nuclear magnetic resonance schemes [3] and photons in both, beam splitter arrays [4] and waveguide structures [5]. The major problem with photonic implementations is the lack of scalability or control over the underlying system. Hence our goal is to circumvent this disadvantages and present a photonic implementation with a high flexibility and scalability.

Quantum Communication, Measurement and Computing (QCMC)
AIP Conf. Proc. 1363, 155-158 (2011); doi: 10.1063/1.3630170

QUANTUM WALK IN AN OPTICAL NETWORK

In this work we present the implementation of a photonic quantum walk with an integrated feedback loop [6] and investigate its scalability. To manipulate the path of the photons in the experiment we use their linear horizontal $|H\rangle$ an vertical polarization $|V\rangle$ as the coin state. Each step of the walk consists of a coin operation $\hat{C}$ acting on the polarization state and a subsequent step operation $\hat{S}$ conditionally moving the photon's wavepacket to a new position $x \rightarrow x \pm 1$. A typical coin operation is the Hadamard gate, transforming the coin state in an equal superposition of basis states. The wavefunction of the photon after n steps of the walk is given by $|\psi_n\rangle = (SC)^n|\psi_0\rangle$ with the initial state $|\psi_0\rangle$. At each step the probability of finding the photon at position x with a coin state c is determined by $P(x,c)_n = |\langle x,c|\psi_n\rangle|^2$.

Functional principle: Experimental setup

Our setup is depicted in Fig.1 (left). An attenuated laser pulse (λ = 805 nm, pulse width = 88 ps) is initialized in an arbitrary polarization state via a half- (HWP) and a quarter-wave plate before getting coupled into the setup with a 3/97 beam splitter (BS_i). For simplicity the initial position is defined as $x = 0$. The polarization of the photon is rotated via another HWP, which constitutes the coin operation $\hat{C}$. By changing the orientation of the HWP's axes we are able to implement quantum walks with completely different coin operations. A separation and recombination of the polarization components via polarizing beam splitters (PBS) leads to a temporal shift determined by an unequal travelled path length. The spread in time is analogous to a spatial step of length ± 1, thus realizing the step operator $\hat{S}$. To implement further steps of the walk without additional optical elements we simply use a loop structure, ensuring that the photon is sent back to the same elements used before. We extract the timing (i.e. position) and polarization information of the photon with two avalanche photo diodes (APDs), by reflecting it out of the setup with a probability of 12% (BS_o) per step. The experiment is repeated with a rate of 110 kHz, allowing to obtain the statistics $P(x,c)_n$ up to a high number of steps.

Scalability: Experimental results

We measured the distribution $P(x,c)_{27}$ after 27 steps of a quantum walk with a symmetric initial state $|H\rangle + \imath|V\rangle$ and the Hadamard coin. A time and polarization analysis reveals the spread of the photon's wavepacket over the resulting 54 output modes (Fig. 1, right). While the probability to end up near the initial position gets suppressed by quantum interference, the outer positions are strictly enhanced. Furthermore, the asymmetric distribution in both coin states is in marked contrast to the symmetric binomial distribution of a classical random walk. This emphasizes the high degree of coherence in the setup. After 27 steps even small inaccuracies of the used optical components have an impact on the fidelity of the final state, compared to the ideal quantum walk. Such

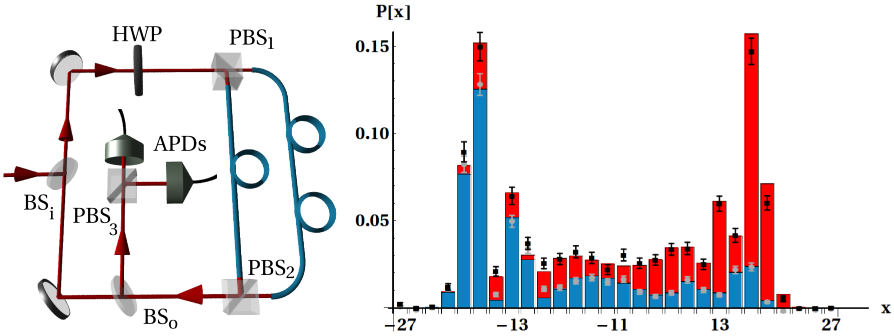

FIGURE 1. Left: Scheme of the setup. The photons get coupled in and out of the setup probabilistically by the beam splitters $BS_{i/o}$. The coin operation is applied via a half-wave plate (HWP). A separation in time induced by two polarizing BS ($PBS_{1,2}$) and polarization maintaining fibers of unequal length implements the step operation. A time and polarization resolving detection is done with two avalanche photodiodes APDs; Right: Arrival distribution $P(x,c)_{27}$ after 27 steps of the symmetric Hadamard walk: Adapted theory for vertical (blue bars) and horizontal polarization (red bars) and measured probabilities (vertical: Gray dots; Vertical + horizontal: Black squares).

imperfections are taken into account in the theory presented in Fig.1 (right). The current limitation of steps is mainly induced by the losses at the optical components: The efficiency per step is equal to 0.55, i.e. a photon will get either lost or detected with a probability of 45% in one round trip. The resulting low arrival rate at the higher step numbers increases the contribution of dark counts detected with the APDs, and hence falsifies the final distribution.

In the following we want to examine in detail the three mentioned limiting factors and give an estimation of their impact on the scalability of the system.

Losses: The losses can be divided into two parts: The intrinsic losses due to in-/ and outcoupling with the beam splitters $BS_{i/o}$ and the common losses at optical components and fiber couplings. To guarantee as many roundtrips as possible, the reflectivity of BS_o can be minimized further, which reduces the probability of a detection at earlier steps. A more efficient way is to replace the passive coupling method by an active switch. In this scheme the photons would be injected in the unused input port of PBS_1. A polarization modulator in each output arm would induce a 90 degree rotation to guide the injected photons to the correct output port of PBS_2. A further active rotation after the desired number of steps would eject the photon at the unused output of PBS_2 for detection.

Since the losses at the optical components are inevitable, a valid method to increase the arrival probability for higher step numbers is to increase the average photon number per initial pulse. We want to emphasize at this point that the quantum interference effect underlying the quantum walk can be simulated with the interference of a coherent light pulse as long as the initial state is localized at one position [7]. A replacement of the laser source with a 1 W Laser and the switch to an active coupling system would give us the possibility to implement 100 steps of the quantum walk.

Accuracy: Based on manufacturing and alignment imperfections the performance of the individual components can influence the quality of the quantum walk. To quantify the overall effect we estimated the degree of accuracy for each component and did a Monte Carlo simulation combining the individual errors. The fidelity of the final state between the ideal walk and the simulation is above 90% for the first 32 steps and drops to 50% for 100 steps, considering a walk with a Hadamard coin and an initial polarization $|H\rangle$.

Decoherence: So far we've realized 27 steps of a quantum walk without a sign of decoherence. One reason to be mentioned here is the intrinsic insensitivity of the setup to static, polarization dependent phase shifts. These are automatically compensated by the geometry of the setup and therefore irrelevant for the coherence of the walk. Nevertheless, dynamic phase fluctuations due to mechanical vibrations still influence the experiment to some extent. Typically, unavoidable vibrations of the optical components occur at a frequency below 500 Hz, corresponding to a time scale of 2 ms. Since the limit of steps is defined by the losses in the setup it is enough to restrict the analysis to 100 steps. The time duration for realizing 100 steps in the current setup would be approximately 50 μs and hence a factor of 20 smaller than the typical vibrations. This means that the impact of decoherence due to vibrations of the optical components is negligible in the first 100 steps.

CONCLUSION

We presented a robust and flexible implementation of a one dimensional coined quantum walk. We demonstrated a low degree of decoherence in the setup by analyzing all 54 output modes after 27 steps of the quantum walk and showed the potential to perform up to 100 steps. The good scalability and control make the setup a perfect test bed for quantum walk based simulations. Furthermore, an addition of another spatial dimension opens up the possibility to implement efficient quantum algorithms, relying on the quantum walk principle.

ACKNOWLEDGMENTS

We acknowledge financial support from the German Israel Foundation (Project 970/2007). K.N.C. and I.J. acknowledge financial support from the Alexander von Humboldt Foundation; V.P., A.G. and I.J. from MSMT LC06002, MSM 6840770039 and CZ-10/2007.

REFERENCES

1. M. Karski *et al.*, Science **325**, 174 (2009).
2. H. Schmitz *et al.*, Phys. Rev. Lett. **103**, 090504 (2009). F. Zähringer *et al.*, Phys. Rev Lett. **104**, 100503 (2010).
3. J. Du *et al.*, Phys. Rev. A **67**, 042316 (2003). C.A. Ryan *et al.*, Phys. Rev. A **72**, 062317 (2005).
4. M. A. Broome *et al.*, Phys. Rev. Lett. **104**, 153602 (2010).
5. Y. Lahini *et al.*, Phys. Rev. Lett. **100**, 170506 (2008). A. Peruzzo *et al.*, Science **329**, 1500 (2010).
6. A. Schreiber *et al.*, Phys. Rev. Lett. **104**, 050502 (2010)
7. P. P. Rohde *et al.*, arXiv:1006.5556v1 [quant-ph] (2010)