Photonic discrete-time quantum walks using spatial light modulators

Graciana Puentes[1,2] and Leonardo Neves[3]

1-CONICET-Universidad de Buenos Aires, Instituto de Fısica de Buenos Aires (IFIBA), Buenos Aires, Argentina
2 Institut Mines-Télécom/Télécom ParisSud-SAMOVAR CNRS UMR5157, 91011 Evry, France
3 Departamento de Física, Universidade Federal de Minas Gerais, Belo Horizonte, MG 31270-901, Brazil

Author e-mail address: gracianapuentes@gmail.com

Abstract: We report a novel scheme for photonic discrete-time quantum walks, using transverse spatial modes of photons and programmable spatial light modulators (SLM). Our scheme enables simulation of arbitrary steps, only limited by the SLM resolution.

OCIS codes: : (270.0270), (270.4180), (270.5585) (230.6120)

The quantum walk is one of the most striking manifestations of how quantum interference leads to a strong departure between quantum and classical phenomena [1]. In its discrete version, namely, the discrete-time quantum walk (DTQW) [2], it offers a versatile platform for the exploration of a wide range of non-trivial geometric and topological phenomena [3-5]. Furthermore, DTQWs are robust platforms for modeling a variety of dynamical processes from excitation transfer in spin chains [6,7] to energy transport in biological complexes [8]. They enable to study multi-path quantum interference phenomena [9-11] and can provide for a route to universal quantum computing [2].

In this contribution, we present a novel scheme for photonic DTQW, using transverse spatial modes of single photons and programmable spatial light modulators (SLM) to manipulate them (Figure 1). Unlike all previous mode-multiplexed implementations, either spatial-multiplexed [14,15] or time-multiplexed [16], this scheme enables simulation of an arbitrary step of the walker, only limited, in principle, by the SLM resolution. It works in an automated way by preparing the input state to the *n*-th step, applying a one-step evolution using the photon polarization as the quantum "coin", and, finally, measuring the probability distribution at the output spatial modes.

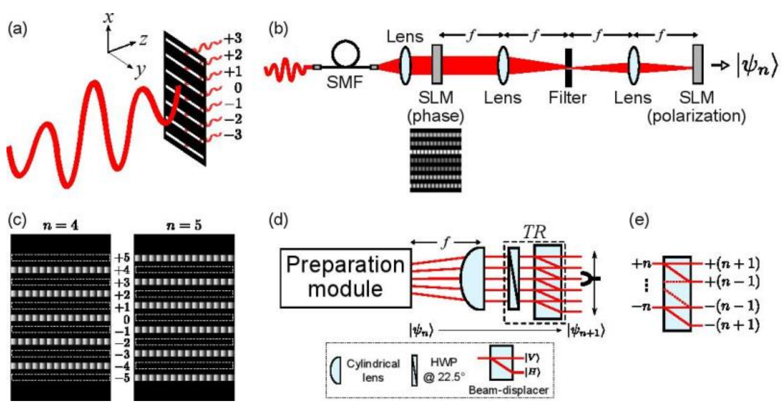


Figure 1. (a) Discretization of a single-photon spatial amplitude profile in transverse modes along the x-direccion. (b) Sketch of the proposed optical setup for preparation of the n-th step walker coin state. (c) Phase masks addressed at the phase-only SLM. (d) Optical module for implementing one step $|\psi_n\rangle \longrightarrow |\psi_{n+1}\rangle$ [18].

A central feature for the operation of our photonic DTQW module will be the use of programmable spatial light modulators. These devices, based on liquid crystal display, consist of a two-dimensional array of pixels, each of which, when properly configured, can control the amplitude, phase or polarization of the incident light field. Let $\psi(r)$ be the quantum state of a paraxial and monochromatic single-photon multimode field horizontally polarized, where $r = (x,y)$ is the transverse position coordinate and $\psi(r)$ is the normalized transverse probability amplitude. By manipulating the transverse amplitude $\psi(r)$ with a phase only SLM, it is possible to prepare arbitrary superpositions of the form $\sum j\ \beta j|j>$ with $\sum j|\beta j|^2 = 1$, where $\{|j>\}$ represent the orthogonal transverse modes in the x-direction [17]. As shown in Figure 1(b), the output state from this scheme is imaged in a second SLM that will control the coin quantum coin state encoded in the photon polarization. Afterwards, the prepared walker-coin state in the *n*-th step goes through the one-step module constituted of a half-wave plate and polarizing beam displacer as sketched in Figure 1(d). With this scheme, will be able to simulate the 1D DTQW for steps (large values of *n*) that cannot be achieved with implementations like time- or spatial-multiplexing.

We discuss current applications of such photonic DTQW architectures in quantum simulation of topological effects [15,16], and extensions of our proposed scheme shown in Figure 1 to the use of non-local coin operations based on two-photon hybrid entanglement [17].

3. References

[1]. Kempe, J. "*Quantum random walks: An introductory overview.*" Cont. Phys. **44**, 307 (2003).
[2]. Aharonov, Y.; Davidovich, L.; Zagury, N. "*Quantum random walks"* Phys. Rev. A **48**, 1687 (1993).
[3]. Kitagawa, T.; Broome, M.A.; Fedrizzi, A.; Rudner, M.S.; Berg, E.; Kassal, I.; Aspuru-Guzik, A.; Demler, E.; White, A.G. "*Observation of topologically protected bound states in photonic quantum walks"*. Nat. Commun. **3**, 882 (2012).
[4]. Kitagawa, T.; Rudner, M.S.; Berg, E.; Demler, E. Exploring topological phases with quantum walks. Phys. Rev. A **82**, 033429 (2010).
[5]. Moulieras, S.; Lewenstein, M.; Puentes, G. "*Entanglement engineering and topological protection in discrete-time quantum walks*". J. Phys. B **46**, 104005 (2013). Featured in Highlights, LabTalk article 53286.
[6].Bose, S. "*Quantum communication through an unmodulated spin chain"*,Phys. Rev. Lett. **91**, 207901 (2003).
[7]. Christandl, M.; Datta, N.; Ekert, A.; Landahl, A.J. "*Perfect state transfer in quantum spin networks*", Phys. Rev. Lett. **92**, 187902 (2004).
[8]. Plenio, M.B.; Huelga, S.F. "*Dephasing-assisted transport: quantum networks and biomolecules*", New J. Phys. **10**, 113019 (2008).
[9]. Spring, J.B.; Metcalf1, B.J.; Humphreys P.C.; Kolthammer, W.S.; Jin, X.M.; Barbieri, M.; Datta, A.; Thomas-Peter, N.; Langford, N.K.; Kundys, D.; *et al*. "*Boson sampling on a photonic chip*", Science **339**, 798–801 (2013).
[10]. Broome, M.A.; Fedrizzi, A.; Rahimi-Keshari, S.; Dove, J.; Aaronson, S.; Ralph, T.C.; White, A.G. "*Photonic boson sampling in a tunable circuit*" Science **339**, 6121 (2013).
[11]. Tillmann, M.; Dakic, B.; Heilmann, R.; Nolte, S. Alexander Szameit and Philip Walther, "*Experimental boson sampling*". Nat. Photon. **7**, (2013).
[12].Broome, M.A.; Fedrizzi, A.; Lanyon, B.P.; Kassal, I.; Aspuru-Guzik, A.; White, A.G. "*Discrete Single-Photon Quantum Walks with Tunable Decoherence*" Phys. Rev. Lett. **104**, 153602 (2010).
[13]. Crespi, A.; Osellame, R.; Ramponi, R.; Giovannetti, V.; Fazio, R.; Sansoni, L.; Nicola, F.D.; Sciarrino, F.; Mataloni, P. "*Anderson localization of entangled photons in an integrated quantum walk."* Nat. Photon. ***7***, 322 (2013).
[14]. Schreiber, A.; Cassemiro, K.N.; Potoˇcek, V.; Gabris, A.; Jex, I.; Silberhorn, C. "*Decoherence and disorder in quantum walks: From ballistic spread to localization*" Phys. Rev. Lett. **106**, 180403 (2011).
[15]. Puentes G. "*Spontaneous Parametric Down Conversion and Quantum Walk Topology*", J. Opt. Soc. Am. B **33**, 461-467 (2016).
[16]. Puentes, G. "*Topology and Holonomy in Discrete-time Quantum Walks*", Crystals **7**, 122 (2017). Selected for Cover Story of special Issue.
[17] L. Neves and G. Puentes, "*Discrete-time Quantum Walks and Applications*", Entropy **20**, 731 (2018). Invited Revie Special Issue.
[18]. Solís-Prosser, M.A. Arias, A Varga, J.J.M., Rebón, L., Ledesma, S., Iemmi, C., Neves, L. "*Preparing arbitrary pure states of spatial qudits with a single phase-only spatial light modulator*", Opt. Lett. **38**, 4762 (2013).

Photonic Discrete-Time Quantum Walks using Spatial Light Modulators

Graciana Puentes[1*] and Leonardo Neves[2]

(1D epartamento de Fisica, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Ciudad Universitaria 1428, Argentina

(2) Departamento de Física, Universidade Federal de Minas Gerais, Caixa Postal 702, Belo Horizonte, MG 30161-970, Brazil

(*) Corresponding author: gpuentes@df.uba.ar

Introduction

- We analyze photonic discrete-time quantum walks (DTQW) using spatial light modulators (SLMs), in combination with bi-photons produced via Spontaneous Parametric Down Conversion (SPDC).
- We analyze the interplay between a non-trivial topology, described by a linear QW Hamiltonian (H_{QW}), on the phase-matching condition characterizing bi-photons produced by of SPDC, described by a non-linear Hamiltonian (H_{SPDC}).
- We propose a novel experimental scheme using SLMs which can enable implementation of DTQWs with an arbitrary number of steps, only limited by the resolution of the SLMs. We present preliminary experimental results
- We propose applications in DTQW with non non-local coin operations

Theoretical Model

2.1 SPDC Hamiltonian (HSPDC)

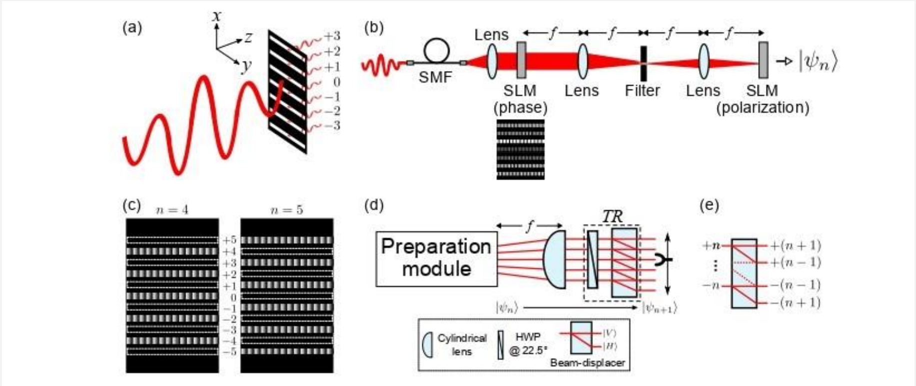
$$H_{\mathrm{SPDC}} = \sum_{p_{s,i}} \int dk_s \int dk_i \Gamma_{p_{s,i}}(k_s, k_i) \hat{A}^{\dagger}{}_{p_s}(k_s) \hat{A}^{\dagger}{}_{p_i}(k_i),$$

2.2 Split-step Quantum Walk Hamiltonian (HQW)

$$H_{QW}(\theta) = \int_{-\pi}^{\pi} dk [E_\theta(k) \vec{n}(k).\vec{\sigma}] \otimes |k\rangle\langle k| \qquad T = \sum_x |x+1\rangle\langle x| \otimes |H\rangle\langle H| + |x-1\rangle\langle x| \otimes |V\rangle\langle V|,$$

$$R_y(\theta) = \begin{pmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{pmatrix} \qquad \phi(k) = \mathrm{atan}\left(\frac{\cos(k)\sin(\theta_1)\cos(\theta_2) + \sin(\theta_2)\cos(\theta_1)}{\sin(k)\sin(\theta_1)\cos(\theta_2)}\right). \quad (2.11)$$

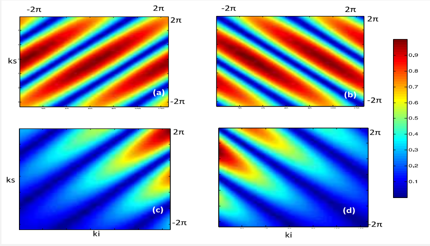
Proposed Experimental Scheme using SLMs



(a)-(d) Experimental set-up for implementation of proposed scheme using spatial qudits generated via SLMs [2]. The advantage of our scheme is that it enables implementation of an arbitrary number of steps (n) only limited by there solution of SLM itself.

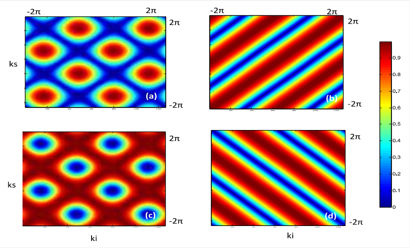
Numerica simulations

(a) Pump Envelope



Numerical simulation of coupling efficiency (Γ) in the Fourier domain.

(b) Phase matching condition



Numerical simulation of coupling efficiency (Γ) in the Fourier domain.

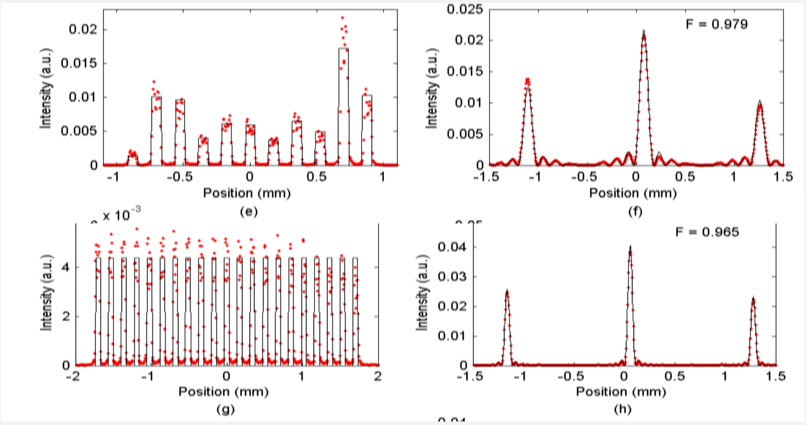
$$\Gamma_{p_{s,i}}(k_s, k_i) = \gamma(E_1^p(k_s+k_i) + E_2^p(k_s+k_i)\frac{n_x(k) + i n_y(k)}{n_z(k) \pm \lambda(k)}).$$

$$\Gamma_{p_{s,i}}(k_s, k_i) = \gamma \sum_{n=1}^{N} E_n^p(k_s+k_i) u_{p_s,j}(k_s) u_{p_i,j}(k_i).$$

$$\Gamma_{p_{s,i}}(k_s, k_i) = \gamma(E_1^p(k_s+k_i) e^{-i|\phi_s(k)+\phi_i(k)|} + E_2^p(k_s+k_i)),$$

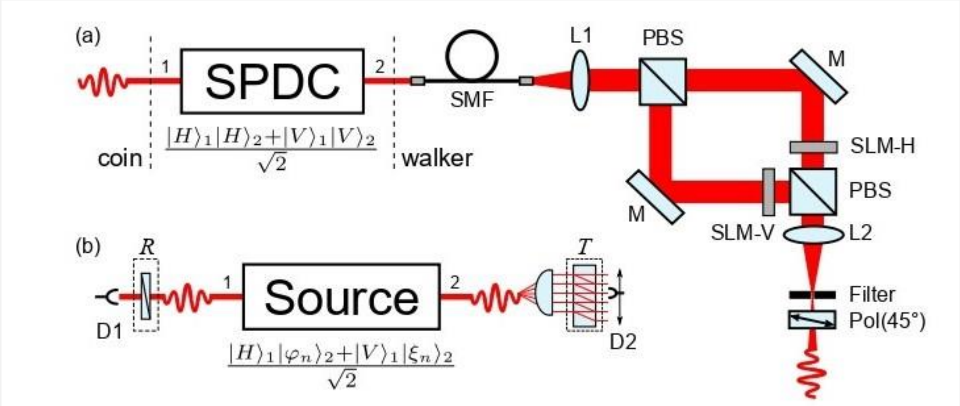
$$\begin{aligned} n^x_{\theta_1,\theta_2}(k) &= \frac{\sin(k)\sin(\theta_1)\cos(\theta_2)}{\sin(E_{\theta_1,\theta_2}(k))} \\ n^y_{\theta_1,\theta_2}(k) &= \frac{\cos(k)\sin(\theta_1)\cos(\theta_2) + \sin(\theta_2)\cos(\theta_1)}{\sin(E_{\theta_1,\theta_2}(k))} \\ n^z_{\theta_1,\theta_2}(k) &= \frac{-\sin(k)\cos(\theta_2)\cos(\theta_1)}{\sin(E_{\theta_1,\theta_2}(k))}. \end{aligned}$$

Preliminary Experimental results



Measured intensity patterns for spatial qudits at image plane (left column) and interference plane (right column) [7].

Applications in DTQW with non-local coins



(a)Schematic of a soure for non-local walker-coin states based on hibrid photonic entanglement [2]. (b) DTQW with non.locat coin operations using this soure.

Discussion

- We proposed a novel scheme for implementation of arbitrary steps (*n*) in discrete-time quantum walks (DTQW) using SLMs.
- We analyzed the interplay between quantum walk (QW) topology and spatial properties of photon pairs produced by SPDC [3].
- As a future work, we expect to characterize the robustness of topological phases and their characteristic bound states against amplitude and phase noise, as well as to decoherence, by tracing over spatial modes of the field.
- One of the main goals is to investigate the use of non-local coin operations, in addition to parametric amplifiers as a means of simulating many-body effects in topological phases. Moreover, we intend to test the feasibility of entanglement engineering and topological protection approaches using DTQW [2,3,4].

Selected References

[1] G. Puentes *et al.*, accepted in OSAC (2020)
[2] L. Neves and G. Puentes, Entopy **20** (2018)
[3] G. Puentes, J. Opt. Soc. Am. B **33** (2016)
[4] S. Moulieras *et al.*, J. Phys. B **46** (2012)
[5] T. Kitagawa *et al.*, Nat. Comm. **3**, 882 (2012)
[7] G. Puentes *et at.*, Phys Rev A . **69,** (2004)

Acknowledgements: The authors gratefully acknowledge financial support from PICT2015-0710, PICT2014-1543, UBACyT PDE 2015, Programa Raices, CONICET, DF FCEyN UBA