Polarization and frequency entanglement for experiments in bulk and integrated optics

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January 27, 2016
Outline

1. Introduction
2. Past Projects
3. Future Projects
Entanglement with Light

- The quantum binary information element is the *Qubit* $|\psi\rangle = \alpha |1\rangle + \beta |2\rangle$
- Imagine two coupled systems represented by their own qubits.
- *Separable State (SS):* The bipartite Hilbert space can be written as tensor product of both density matrices $\rho = |\psi\rangle \langle \psi|$. 
- *Entangled State (ES):* Opposite to the SS, e.g. $\rho_{1,2} \neq \rho_1 \otimes \rho_2$.

- **Polarization Entanglement (PE):** Encodes qubits in the light polarization basis.
  \[
  |\psi\rangle = \alpha |H\rangle_1 |V\rangle_2 + \beta |V\rangle_1 |H\rangle_2 \tag{1}
  \]
- **Polarization-Frequency Entanglement (PFE):** Like PE, but adding distinguished light wavelengths to each polarization mode.
  \[
  |\psi\rangle = \alpha |H\rangle_{\lambda_1} |V\rangle_{\lambda_2} + \beta |V\rangle_{\lambda_1} |H\rangle_{\lambda_2} \tag{2}
  \]
Optical Source of Entanglement

Spontaneous Parametric Down Conversion (SPDC)

Type-II SPDC

- A pumping photon excites a valence electron of a non-linear crystal.
- When the electron decays two photons emerge, but with new wavelengths.
- The process conserve energy $\omega_p = \omega_s + \omega_i$ and momentum $\mathbf{k}_p = \mathbf{k}_s + \mathbf{k}_i$
- Ordinary polarized pump generates photons with orthogonal polarizations (ordinary and extraordinary).

Quasi-Phase-Matching in Periodic Poled KTP compound

- Periodically alternate non-linear index
- Keeps only the positive phase contributes of the SPDC along the crystal.
Sagnac Source of Entangled Photons

- Compensates optical paths phase difference between the clockwise and anti-clockwise beams.

- Pump power-polarization control
- Double SPDC for the generation indistinguishability and entanglement.
- Active oven for the temperature control, and inclination control for the collinearity.
- Tomography stages and customizable focalization.
Improving the entanglement source quality

Changes

- Singlemode laser
- PM optical fiber
- Spatial filter by pinhole
- Erasure of diffraction rings
- Crystal focalization
- Interference filters of $FWHM = \pm 3[nm]$
- Telescope optimization

<table>
<thead>
<tr>
<th>Pumping at 2,5[mW]</th>
<th>Concurrence [%]</th>
<th>Fidelity [%]</th>
<th>Single. C. [$\frac{1}{5}$]</th>
<th>Coin. C. [$\frac{1}{5}$]</th>
<th>Spec. Band [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old Source</td>
<td>96,5</td>
<td>95</td>
<td>46900</td>
<td>4600</td>
<td>5</td>
</tr>
<tr>
<td>New Source</td>
<td>98</td>
<td>98,5</td>
<td>337500</td>
<td>61500</td>
<td>0,5</td>
</tr>
</tbody>
</table>
Non-Markovian Dynamics

- Sequence of two system-environment interactions
- Loss of original information (entanglement with an ancilla)
- Backflow of information or Non-Markovian (NM) dynamics.
- NM: non positive or completely positive decomposition of a system evolution operator.
- WNM: non completely positive decomposition of a system evolution operator.
Identification of a "‘Weak Non-Markovianity’" (WNM), unseen by the traditional information backflow techniques.
Amendable Channels

Amending Entanglement Breaking Maps (EBM)

- An EBM\(^n\), applied \(n\)-times destroy the entanglement between a sample system and an ancilla.
- Suppose a map \(\Psi_s \in EBM^2\) composed by a Half Wave Plate (HWP) after an Amplitude Damping Channel.
- Suppose a map \(\Phi_s \in EBM^2\) composed by an ADP after a HWP.
- Then, \(\Psi_s \circ \Psi_s(\rho_s,a)\), \(\Phi_s \circ \Phi_s(\rho_s,a)\) and \(\Phi_s \circ \Phi_s \circ \Psi_s \circ \Psi_s(\rho_s,a)\) destroy entanglement.

Amendable Channel by Filter Map

- \(\Psi_s \circ \Theta_s \circ \Psi_s(\rho_s,a) \notin EBM^2\)
- Where \(\Theta_s\) is the Filter map composed by two consecutive HWPs.

Amendable Channel by Cut & Paste Map

- \(\Phi_s \circ \Psi_s \circ \Phi_s \circ \Psi_s(\rho_s,a) \notin EBM^2\)
Amendable Channels

Amplitude Damping Channel (ADC)

\[ \alpha |H\rangle \rightarrow \alpha |H\rangle \]
\[ \beta |V\rangle \rightarrow \beta (\sqrt{\eta} |V\rangle + \sqrt{1-\eta} \alpha |H\rangle) \]

\[ E_1 = \begin{pmatrix} 1 & 0 \\ 0 & \sqrt{\eta} \end{pmatrix} \]
\[ \text{and} \]
\[ E_2 = \begin{pmatrix} 0 & \sqrt{1-\eta} \\ 0 & 0 \end{pmatrix} \]

Filtered Channel Scheme

![Diagram of filtered channel scheme](image)
Cut And Paste Channel Scheme

\[ \varphi = \pi/4 \quad \eta_1 = \eta_2 = 0.3 \quad \theta \in \left[-\pi/2, \pi/2\right] \]

**Legend**
- Fiber coupler
- PBS
- BS
- Mirror
- PC
- HWP
- QWP
- LCD
- SPAD
- Beam-stop

**Detection stage**
- SMF
- CC Box
Lower bounds to the Quantum Channel Capacity ($Q$)

- In noisy quantum communication channels

\[
Q > Q_{\text{Detectable}} = S \left( \epsilon \left( \frac{I}{d} \right) \right) - H(\bar{p})
\]  

- $S(\rho) = -\text{Tr}[\rho \log_2(\rho)]$ is the Von Neumann Entropy
- $H(x) = -x \log_2(x) - (1 - x) \log_2(1 - x)$ is the Shannon Entropy
- $\epsilon(\rho) = \sum_j A_j \rho A_j^\dagger$ is the noisy channel operator.
• $H$ must be minimized by some optimized parameters,
• One has to measure $\sigma_x^s \otimes \sigma_x^a$, $\sigma_y^s \otimes \sigma_y^a$ and $\sigma_z^s \otimes \sigma_z^a$,
• A considerable reduction in the number of measurements compared with a tomography.
Super-diffusion of Photons in randomly diluted Quantum Walks (QW)

- In a network of Mach-Zehnder (MZ) interferometers, where each step is considered as an integrated QW, transmitted input photons choose sequentially which output to take.
- The length differences between MZ’s arms is equivalent to a phase difference.
- Ordered QW: For any step the MZ’s phase differences are zero, transporting geometrically diffused light.
- Static Disordered QW: For any step the phases present a statistical static disorder, transporting non diffusive light.
- Anderson Localization
Quantum Walks in Integrated Photonics

**Known Diffusion or Anderson Localization for Single Photons**

![Diagram of a quantum walk](image)

**Known Diffusion or Anderson Localization for Entangled Photons**

![Diagram of a quantum walk in entangled photons](image)
A quantum process $\Phi$ is defined to be Markovian if the Trace Distance (TD) between two biased mapped states

$$||p_1 \Phi_t(\rho_1) - p_2 \Phi_t(\rho_2)||_1 = Tr|p_1 \Phi_t(\rho_1) - p_2 \Phi_t(\rho_2)|$$  \hspace{1cm} (6)$$
decrease with $t \geq 0$.

We define $l_{int} = ||p_1 \Phi_S^1(t) - p_2 \Phi_S^2(t)||_1$ and $l_{ext} = ||p_1 \Phi_S^1(t) - p_2 \Phi_S^2(t)||_1$ correlated by the information relation $l_{int}(t) + l_{ext}(t) = l_{int}(0) = cons$

Quantifying the degree of memory effects by continuity in $t$ we get a new TD

$$N(\Phi) = \max \{p_i\}, \rho_2 \in \partial U(\rho_1) \int_{\sigma > 0} dt \sigma(t, p_i \rho_i)$$  \hspace{1cm} (7)$$

Where $\sigma(t, p_i, \rho_i) \equiv \frac{1}{||p_1 \rho_1 - p_2 \rho_2||_1} \frac{1}{dt} ||p_1 \Phi_t(\rho_1) - p_2 \Phi_t(\rho_2)||_1$.  

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P-divisibility is no more enough to prove Markovianity, we need to use also CP-divisibility.

The idea of the work is to measure the generalized trace distance of two states before and after some map.

If the TD weights are \( p_1 = p_2 \) we are not able to detect non-Markovianity.

If the TD weights are \( p_1 \neq p_2 \) (under some restrictions) we are able to detect non-Markovianity.

Confirmation of a local and universal representation of the measure of Markovianity.
Thank you for your attention!!!