Quantum information in the Joint Laboratory of Optics
last three years of photon pairs

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Optics in Olomouc

- optics in Olomouc celebrates 50 years

- JMO (local journal – fine mechanics and optics) topical issue 2012/1

- Department of Optics

- Joint Laboratory of Optics

- cooperation with a number of industrial and academic partners

- collaboration in large international teams (CERN, Pierre Auger)

- Research fields:
  - applied optics
  - classical optics
  - quantum optics
Quantum information in the Joint Laboratory of Optics

- first experiments in late 90s
- physical platform: photon pairs + linear optics
- QIP topics: quantum cryptography, quantum gates and various other QIP protocols

this talk: recent QIP experiments
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Knill-Laflamme-Milburn states

- **Linear optics is suitable** for various QIP tasks:
  - Quantum cryptography
  - Quantum gates
  - Quantum teleportation

- Problem: **Low efficiency**, prevents **scaling** of the gates

- Proposed solution: **Specific quantum states**

  \[
  |\Psi_{KLM}\rangle = \sum_{j=0}^{n} \alpha_j |1angle^j |0\rangle^{n-j}, \text{ where } |0\rangle, |1\rangle \text{ denote logical states}
  \]

- In principle these states allow to **increase considerably** success probability

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we aim on preparing special two-photon class of these states

\[ |\Psi_{2\text{pKLM}}\rangle = \gamma |11\rangle + \delta |10\rangle + \gamma |00\rangle = \gamma |H_1 V_1\rangle + \delta |H_1 V_2\rangle + \gamma |H_2 V_2\rangle \]

theoretical proposal for preparation:


no post-selection required (deterministic)

requires partially entangled input state
Experimental implementation

- Pair of BBO type I crystals used to generate polarization entangled photon pairs (Kwiat source)
- Preparation takes place on the first beam splitter (tunable)
- Second beam splitter used for analysis
Experiment results

- successful preparation and analysis of KLM states
- density matrices were estimated
- $|\gamma/\delta|^2$ ratio plotted as a function of experiment setting (parameter $\alpha$)
- fidelity about 92%

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c-phase gate - an important QIP building block

theoretical proposal:

K. Kieling, J. L. O’Brien, J. Eisert

several advantages:

- tunable phase shift \([0, \pi]\)
- optimal for every phase shift
- first study of success probability as a function of phase shift

C-phase gate

| |00\rangle |00\rangle 
| |01\rangle |01\rangle 
| |10\rangle |10\rangle 
| |11\rangle \rightarrow e^{i\varphi}|11\rangle
Experimental implementation

- polarization encoding + cc. post-selection
- BDA – convenient way to introduce polarization sensitive losses and phase shifts
- 3 nested MZ interferometers + HOM dip
Experiment results

- process tomography for 7 different phase shifts
- process Choi matrices estimated – process fidelities about 90%
- verified non-monotonous behaviour of success probability

Why is the success probability non-monotonous?

answer: in order to achieve state independent success probability, one has to set specific phase shift in the MZ interferometer.

cc. rate depends on MZ interferometer phase shift (interference fringe) and its visibility (different losses required for different gate phase shifts).

C-phase gate as a source of KLM states

- using **non-tunable** gate to generate KLM states:

- the tunability **allows to increase the success probability** of preparation

- does not require entangled input state

How to describe the entangling capability of a probabilistic gate?

**entangling power** –
\[ E_p = \max_{\hat{\rho}_{in}} \{ N(\hat{\rho}_{out}) \} \]

problem: does not take into account the success probability

**solution:** **entangling efficiency** –
\[ E_{eff} = \max_{\hat{\rho}_{in}} \{ P_s(\hat{\rho}_{in}) N(\hat{\rho}_{out}) \} \]

gives the entanglement yield

allows to find optimal gate setting and input state

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Polarization dispersion noise

- specific noise caused by fluctuations of polarization dispersion

\[
\begin{align*}
n_H \neq n_V : |HV\rangle + |VH\rangle &\rightarrow |HV\rangle + e^{i\phi}|VH\rangle
\end{align*}
\]

- impact on entanglement distribution – phase noise

- leads to mixed state

- phase flip (or bit flip) errors

- compact characterization device:

Goal of the experiment

- simulate various amounts (statistics) of phase noise

**Target state**

\[ \hat{\rho}_{\text{noisy}} = \int_{\Omega} p(\phi) |\Psi(\phi)\rangle\langle \Psi(\phi)| d\phi, \text{ where } |\Psi(\phi)\rangle = \left( |HV\rangle - e^{i\phi} |VH\rangle \right) / \sqrt{2} \]

- there are already several implementations, but with limitations
  - use of birefringent material – phase correlated with wavelength
  - use of interferometer – need for stabilization

- our implementation:
  - noise should not be correlated with other degree of freedom (spectrum)
  - easy and stable implementation (avoid interferometric stability)
random swap between 2 positions (using QWP)

\[ \hat{\rho}_{\text{noisy}} = \frac{\langle \Psi(\delta \varphi) | + \langle \Psi(-\delta \varphi) \rangle}{2} \]

mimics realistic noisy density matrix
Experiments results

- simulation of two statistics (const. step, Gauss.)

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Theoretical design

- quantum cloning limited by the no-cloning theorem

- **single purpose cloner** – clones with respect to one type of a priory information (universal, phase-covariant)

- **multifunctional cloner** – can incorporate several types of a priory informations

- provides several cloning regimes

- theoretical design:

Cloning regimes

- a) universal, b) phase-covariant, c) mirror phase-covariant, d) general symmetrical statistics
Experimental implementation
Results

- device reaches 97.5% of theoretical fidelity
- first ever implementation of mirror phase-covariant cloning

Applications of multifunctional cloner

- optimal attack on quantum key distribution protocols
- several protocols can be attacked by the same setup
- we are currently working on optimal attack on spherical code QKD
- simulation of Pauli damping channels

Conclusions

Thank you for your attention.