Experimental characterization of a non-local convertor for quantum photonic networks

M. Mičuda[1], R. Stárek[1], P. Marek[1], M. Miková[1], I. Straka[1], M. Ježek[1], T. Tashima[2], Ş. K. Özdemir[3], and M. S. Tame[2]

[1]Department of Optics, Palacký University, 17. listopadu 1192/12, 771 46 Olomouc, Czech Republic
[2]School of Chemistry and Physics, University of KwaZulu-Natal, Durban 4001, South Africa
[3]Department of Electrical and Systems Engineering, Washington University in St. Louis, St. Louis, MO 63130 USA

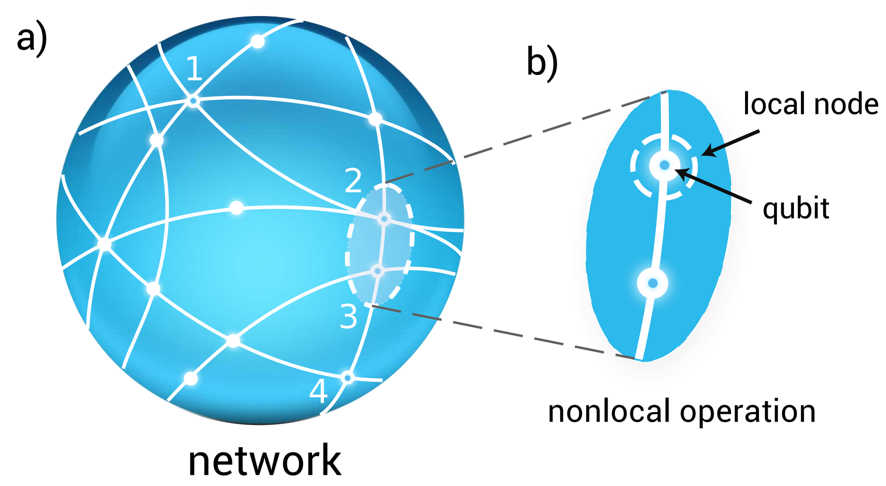
Abstract

We experimentally characterize a quantum photonic gate that is capable of converting multiqubit entangled states while acting only on two qubits. We show the conversion of a linear four-qubit cluster state into different entangled states, including GHZ and Dicke states. The gate can also be used to generate quantum information processing resources such as entanglement and discord.

General principle

Global state of a large quantum network can be changed by small-scale manipulation of local nodes [1]:
a) Quantum network with restricted access to 2[nd] and 3[rd] local node. In our results we show as an example four-qubit entangled states.

b) Conversion gate that operates on qubits in local nodes 2 and 3 of the quantum network. It enables the conversion of diferent types of multipartite entangled states for quantum networking applications.

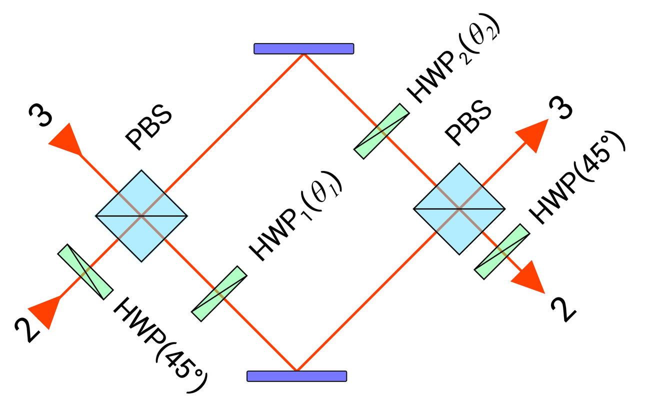


Linear cluster state

$$|C_4\rangle = \tfrac{1}{2}(|HHHH\rangle + |HHVV\rangle + |VVHH\rangle - |VVVV\rangle)$$

Nonlocal conversion gate

using linear optics and polarization encoding [2]



Gate operator:

$$\begin{aligned} G(\theta_1,\theta_2) &= (\alpha_1-\beta_1)\,|HH\rangle_{out\ in}\langle HH| \\ &+ (\alpha_2-\beta_2)\,|VV\rangle_{out\ in}\langle VV| \\ &+ \mu_1\,|HV\rangle_{out\ in}\langle HV| - \mu_2\,|HV\rangle_{out\ in}\langle VH| \\ &+ \mu_1\,|VH\rangle_{out\ in}\langle VH| - \mu_2\,|VH\rangle_{out\ in}\langle HV| \end{aligned}$$

Where: $\alpha_k = \cos^2(2\theta_k)$ $\quad \mu_1 = \cos(2\theta_1)\cos(2\theta_2)$
$\beta_k = \sin^2(2\theta_k)$ $\quad \mu_2 = \sin(2\theta_1)\sin(2\theta_2)$

Linear cluster state

$$|C_4\rangle = \tfrac{1}{2}(|HHHH\rangle + |HHVV\rangle + |VVHH\rangle - |VVVV\rangle)$$

Four qubit GHZ state

$$|GHZ_4\rangle = \tfrac{1}{\sqrt{2}}(|HHHH\rangle + |VVVV\rangle)$$

Dicke state

$$\left|D_4'^{(2)}\right\rangle = \frac{1}{\sqrt{6}}(|HHHH\rangle + |VVVV\rangle - |HHVV\rangle - |VVHH\rangle + |HVHV\rangle + |VHVH\rangle)$$

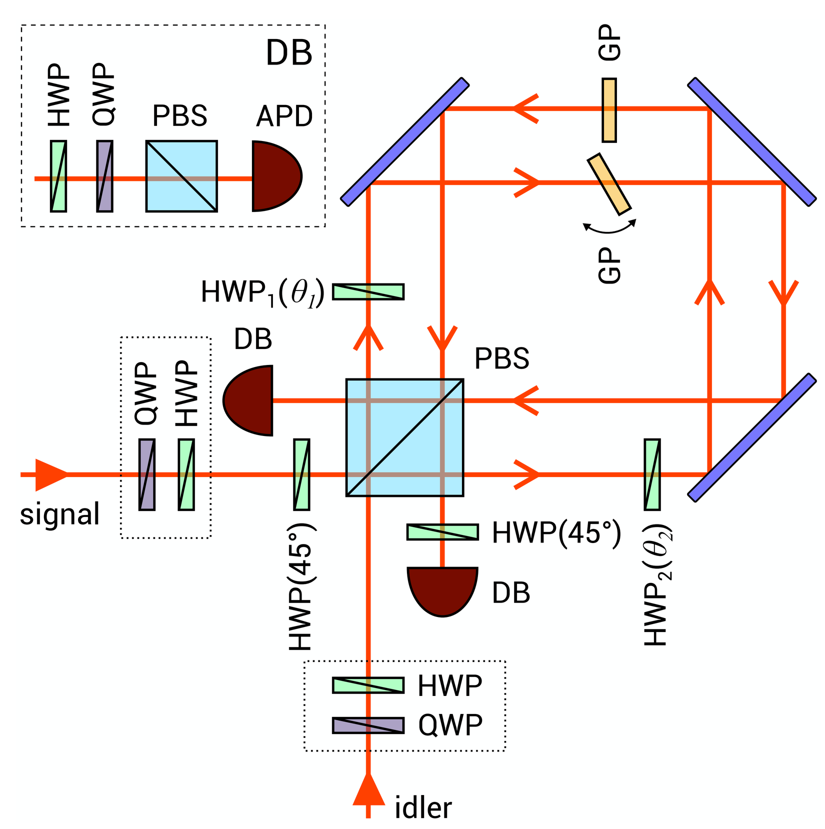
using local operations $\sigma_z \otimes \sigma_x \otimes \sigma_z\sigma_x \otimes \mathbb{I}$ gives

$$\left|D_4^{(2)}\right\rangle = \frac{1}{\sqrt{6}}(|HVVH\rangle + |VHHV\rangle + |HVHV\rangle + |VHVH\rangle + |HHVV\rangle + |VVHH\rangle)$$

Two Bell states

$$|\Psi^+\rangle_{14}|\Psi^+\rangle_{23} = (|HV\rangle_{14} + |VH\rangle_{14})(|HV\rangle_{23} + |VH\rangle_{23})$$

Experimental setup

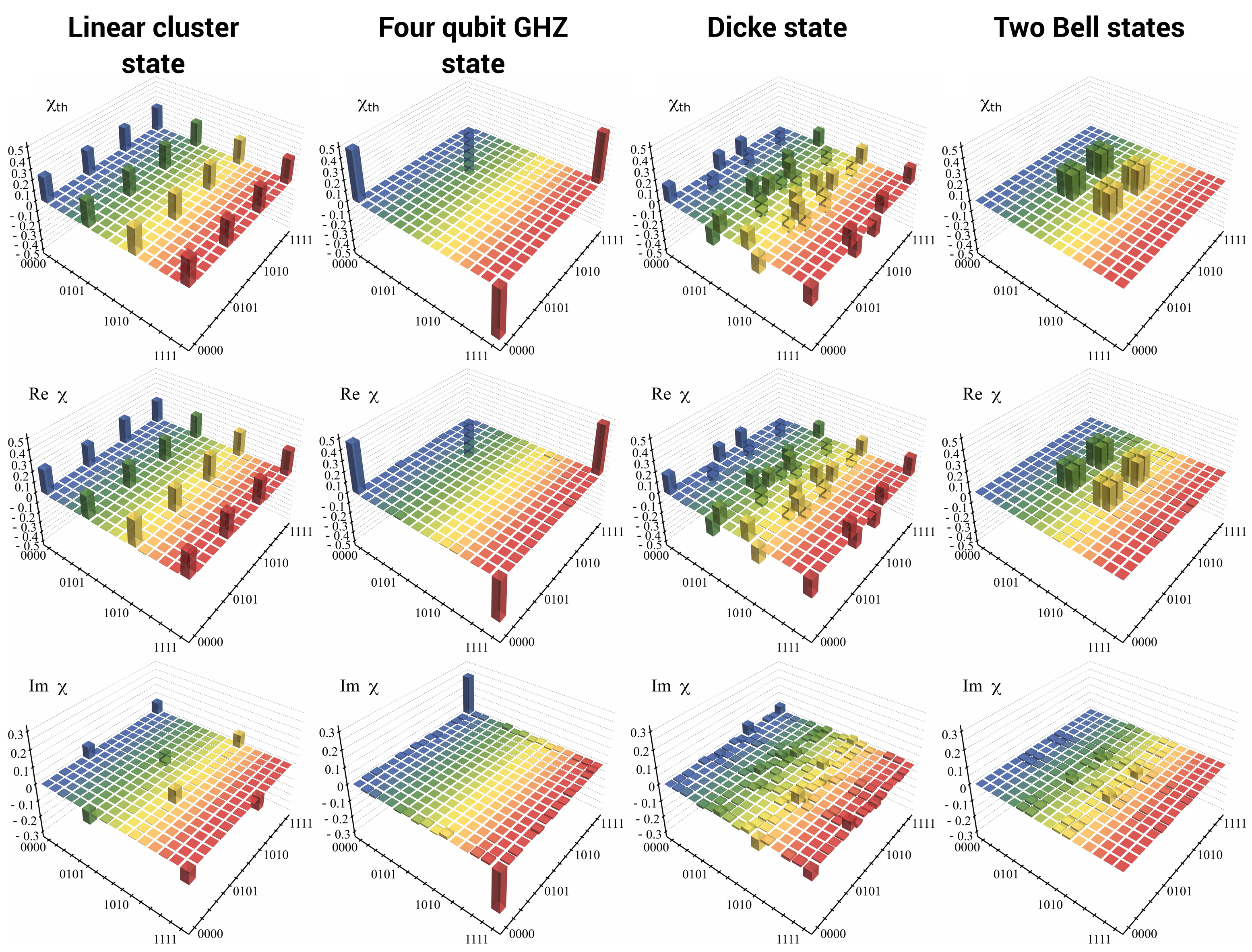


We used source of time-correlated photon pairs generated by SPDC process. The interferometric phase in the displaced Sagnac interferometer was controlled by tilting one of the glass plates (GP). The dotted boxes represent preparation stages for encoding different inputs. The dashed box represents the analysis stages (DB) for characterizing the output states of the gate.

QWP - quarter-wave plate
HWP - half-wave plate
PBS - polarizing beam splitter
GP - glass plate
DB - detection block
APD - avalanche photodiode

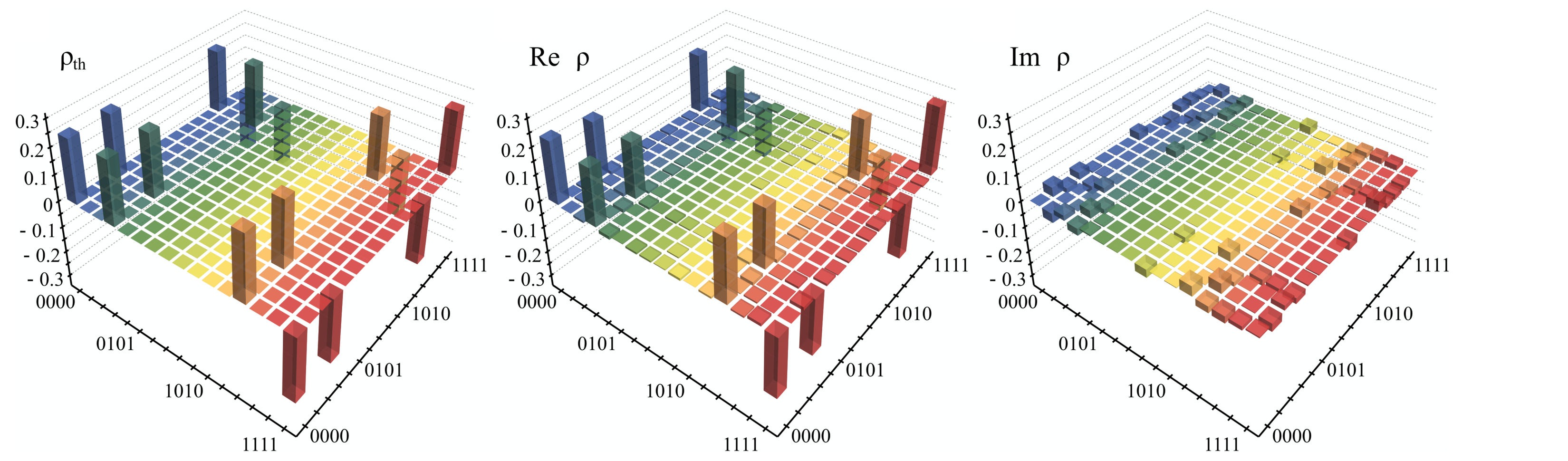
Results

Reconstructed process matrices χ of the conversion gate using the Choi-Jamiolkowski representation. The matrices are written in the polarization basis of the input and output Hilbert spaces $(\{|0\rangle,|1\rangle\} \leftrightarrow \{|\mathrm{H}\rangle,|\mathrm{V}\rangle\})$. Calculated process purity P, process fidelity F_χ, success probabilities p_s, and the maximal theoretical success probabilities $p_{s,max}$ of the non-local conversion gate are given below.



Linear cluster state	Four qubit GHZ state	Dicke state	Two Bell states
P = 0.949(1)	P = 0.913(3)	P = 0.917(2)	P = 0.920(2)
F_χ = 0.973(1)	F_χ = 0.952(2)	F_χ = 0.948(1)	F_χ = 0.953(1)
p_s = 1	p_s = 1/2	p_s = 3/10	p_s = 1/4
$p_{s,max}$ = 1	$p_{s,max}$ = 1/2	$p_{s,max}$ = 3/4	$p_{s,max}$ = 1/2

Conversion gate in realistic scenario:
We employed the reconstructed process matrices χ of the two-qubit conversion gate and numerically simulated its effect on a realistic version of a four-qubit linear cluster state with density matrix ρ generated in a four-qubit linear-optical quantum logic circuit [3]. The fidelity of the cluster state has value of F = 0.915.



Numerically simulated fidelity of the output states converted from the realistic linear cluster state, where operational fidelity measures the overlap between the realistic state transformed by the experimental conversion gate and the ideal theoretical conversion gate. The total fidelity measures the overall fidelity between the realistic state transformed by the experimental conversion gate and the ideal state transformed by the ideal theoretical conversion gate.

Product of the conversion	Fidelity (operation)	Fidelity (total)
Cluster state	0.98	0.87
GHZ state	0.99	0.89
Dicke state	0.97	0.84
Two Bell states	0.97	0.91

Other uses of the conversion gate:
1) We can use the conversion gate to transform two-qubit factorized state into entangled state. We generated maximally entangled Bell state $|\Phi^+\rangle = (|HH\rangle + |VV\rangle)/\sqrt{2}$ by preparing input state $|--\rangle$. The generated state purity was P = 0.946(7) and state fidelity was F = 0.966(3).

2) We can use conversion gate to prepare a separable state with non-zero quantum correlations that can be measured by the discord. Preparing a mixed factorized state $\rho_{in} = \frac{1}{2}\mathbb{I} \otimes |+\rangle\langle+|$ as an input state. To prove separability of the measured state we used logarithmic negativity LN and concerrence C [4]. Obtained LN = 0.019(20) and C = 0.015(15) show values separated from zero by less than one standard deviation while measured discord D = 0.066(7) [5] is significantly positive.

References

[1] T. Tashima, M. S. Tame, Ş. K. Özdemir, F. Nori, M. Koashi, and H. Weinfurter, Phys. Rev. A **94**, 052309 (2016).
[2] M. Mičuda, R. Stárek, P. Marek, M. Miková, I. Straka, M. Ježek, T. Tashima, Ş. K. Özdemir, and M. S. Tame, Optics Express **25**, 7839 (2017).
[3] R. Stárek, M. Mičuda, M. Miková, I. Straka, M. Dušek, M. Ježek, and J. Fiurášek, Sci. Rep. **6**, 33475 (2016).
[4] R. Horodecki, P. Horodecki, M. Horodecki, and K. Horodecki, Rev. Mod. Phys. **81**, 865 (2009).
[5] K. Modi, A. Brodutch, H. Cable, T. Paterek and V. Vedral, Rev. Mod. Phys. **84**, 1655 (2012).

Acknowledgments

M. M., R. S., M. Miková, I. S. and M. J. acknowledge support from the Czech Science Foundation (GA16-17314S). P. M. acknowledges support from the Czech Science Foundation (GB14-36681G). T. T. and M. T. acknowledge support from the South African National Research Foundation and the South African National Institute for Theoretical Physics.