Generation of time-frequency grid state with integrated biphoton frequency combs

Nicolas Fabre[1,3], Giorgio Maltese[1], Felicien Appas[1], Simone Felicetti[1], Andreas Ketterer[2], Maria Amanti[1], Florent Baboux[1], Arne Keller[1], Thomas Coudreau[1], Sara Ducci[1] and Perola Milman[1]

[1]*Laboratoire Matériaux et Phénomènes Quantiques, Sorbonne Paris Cité, Université de Paris, CNRS UMR 7162, 75013 Paris, France*
[2]*Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Str. 3, 79104 Freiburg, Germany*
[3]*Centre of New Technologies, University of Warsaw, Banacha 2c, 02-097 Warszawa, Poland*

*Abstract: Encoding quantum information in continuous variables is intrinsically faulty. Nevertheless, redundant qubits can be used for error correction, as proposed by Gottesman, Kitaev and Preskill in Phys. Rev. A **64** 012310, (2001). We show how to experimentally implement this encoding using time-frequency continuous degrees of freedom of photon pairs produced by spontaneous parametric down conversion. Our theoretical model relies on the analogy between operations involving multi- photon states in one mode of the electromagnetic field and single photons occupying many modes. We illustrate our results using an integrated AlGaAs platform, and show how single qubit gates and error correction can be experimentally implemented in a circuit-like and in a measurement-based architecture.*

Time-frequency GKP state: a new qubit in the time-frequency continuous variables degree of freedom of single photons

Time-frequency formalism of single photon

Displacement in frequency-time phase space

$$\hat{D}(\mu) = \int d\omega \hat{a}^\dagger(\omega+\mu)\hat{a}(\omega)$$

$$\hat{\mathcal{D}}(\tau) = \int dt \hat{a}^\dagger(t+\tau)\hat{a}(t)$$

Similar to the position-momentum displacement operator

$$\hat{D}(x) = e^{ix\hat{p}}$$

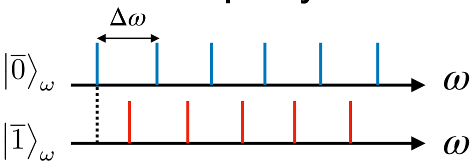
$$\hat{D}(p) = e^{ip\hat{x}}$$

Weyl's algebra $\hat{D}(\mu)\hat{\mathcal{D}}(\tau) = e^{i\mu\tau}\hat{\mathcal{D}}(\tau)\hat{D}(\mu)$ $\quad \hat{D}(x)\hat{D}(p) = \hat{D}(p)\hat{D}(x)e^{-ipx/2}$

The non-commutative algebra comes from:

$$[\hat{a}(\omega'), \hat{a}^\dagger(\omega)] = \delta(\omega-\omega') \quad \textbf{and} \quad [\hat{a}, \hat{a}^\dagger] = \mathbb{I}$$

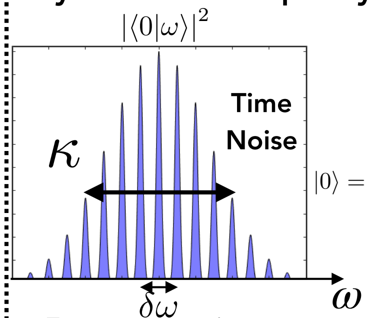
Ideal Time-Frequency GKP state



$$|\bar{0}\rangle_\omega = \sum_{n\in\mathbb{Z}} |2n\Delta\omega\rangle \quad |\bar{1}\rangle_\omega = \sum_{n\in\mathbb{Z}} |(2n+1)\Delta\omega\rangle$$

$$|\bar{\pm}\rangle_\omega = \frac{1}{\sqrt{2}}(|\bar{0}\rangle_\omega \pm |\bar{1}\rangle_\omega)$$

Physical Time-Frequency GKP state

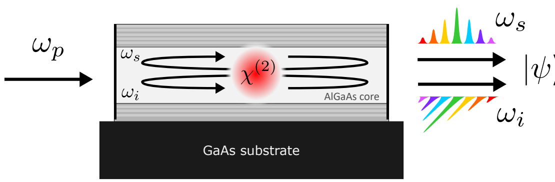


$$|0\rangle = \hat{K}\,|\bar{0}\rangle$$

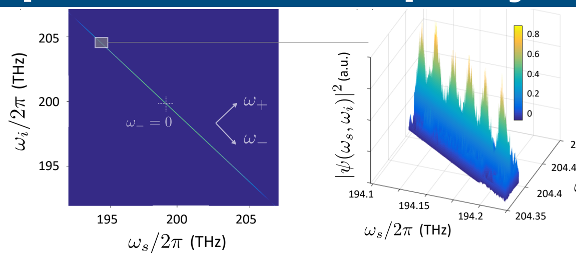
Kraus operator

$$|0\rangle = \iint D(\omega)D(t)G_\kappa(t)G_{\delta\omega}(\omega)\,|\bar{0}\rangle$$

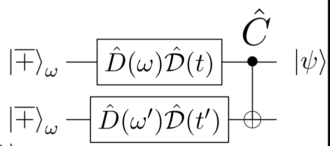
Creation and Manipulation of time-frequency GKP states



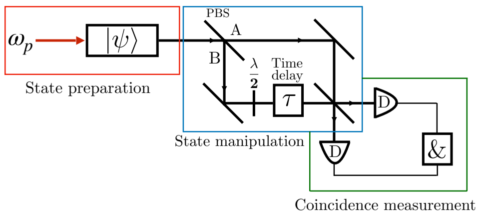
A pump beam illuminates an AlGaAs waveguide where photon pairs are generated by SPDC.



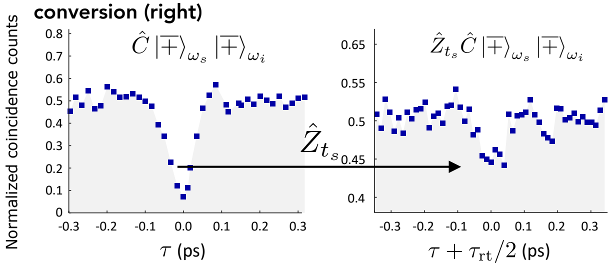
Simulated JSI of the state emitted by the nonlinear cavity (left). Experimental JSI, with stimulated parametric down conversion (right)



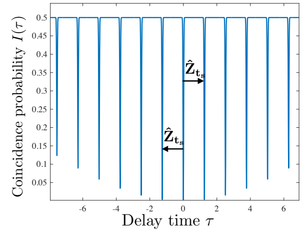
Quantum circuit to interpret the generation of the entangled GKP state.



HOM interferometer. A time delay performs a one qubit Gate



Experimental coincidence measurement $(R = 0.3)$



Numerical coincidence measurements $(R = 0.9)$

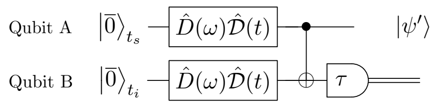
Quantum error correction

Noise model

<u>Time Noise:</u> **Temporal dispersion**

<u>Frequency Noise</u>: **Broadening in Atomic frequency memory comb Or polarisation mode dispersion**

Steane error correction



Correction of the temporal noise coming from the generation itself
Preparation of a time-frequency GKP state by conditional measurement

References

(1) D. Gottesman, A. Kitaev, and J. Preskill, Phys. Rev. A **64**, 012310 (2001).
(2) Y. J. Lu, R. L. Campbell, and Z. Y. Ou, Phys. Rev. Lett. **91**, 163602 (2003).
(3) N. Fabre, G. Maltese, F. Appas, S. Felicetti, A. Ketterer, A. Keller, T. Coudreau, F. Baboux, M. I. Amanti, S. Ducci, and P. Milman, *Generation of a Time-Frequency Grid State with Integrated Biphoton Frequency Combs*, Phys. Rev. A **102**, 012607 (2020).