Novel source of multimode squeezed light for quantum enhanced space-time positioning

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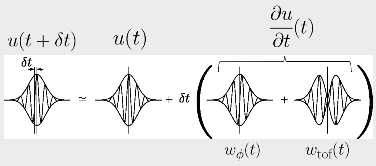
We present a new multimode squeezed-states quantum source operating in a single pass regime suitable for ultimate precision space-time positioning experiments.

Space-time Positioning

Finding out position in space by ranging to a reference.
Measurement of time delay changes δt in a reflected pulse.



Choice of detection mode

Coherent interferometric phase measurement

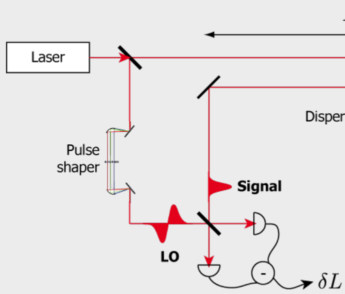
$$w_{LO} = w_\phi(t)$$

$$(\delta t)^{\text{phase}} = \frac{1}{2\sqrt{N}\omega_0}$$

Incoherent time-of-flight measurement

$$w_{LO} = w_{\text{tof}}(t)$$

$$(\delta t)^{\text{tof}} = \frac{1}{2\sqrt{N}\Delta\omega}$$



Enhncement of accuracy using the complete detection mode in homodyne detection [3]

Detection mode

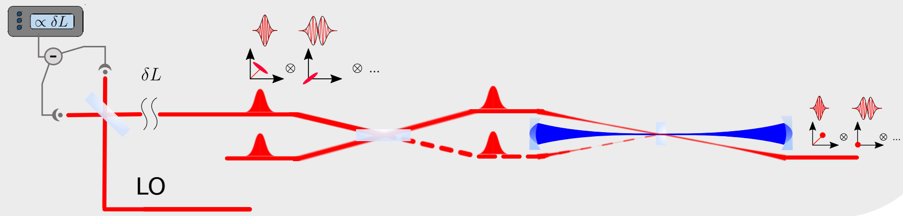
$$w_L(\omega) = \frac{1}{\sqrt{\frac{\omega_0^2}{v_\phi^2} + \frac{\Delta\omega^2}{v_g^2}}}\left(\frac{\omega_0}{v_\phi}w_\phi(\omega) + \frac{\Delta\omega}{v_g}w_{\text{tof}}\right)$$

Minimum resolvable distance

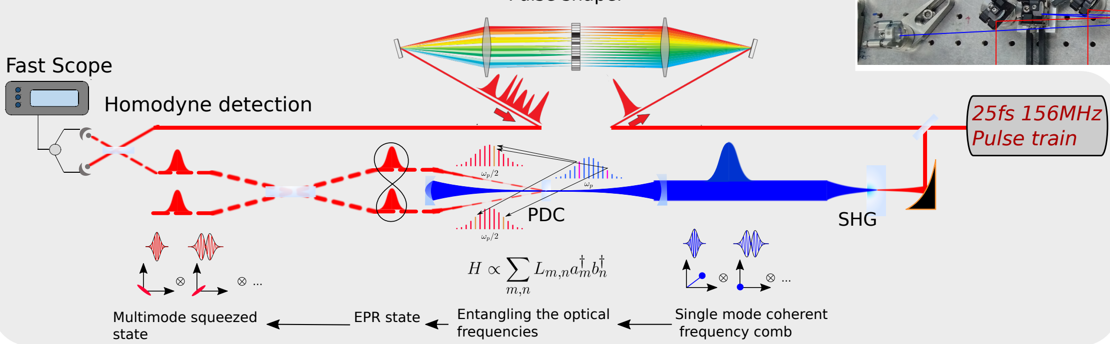
$$\delta L_{min} = \frac{1}{2\sqrt{N}}\left(\left(\frac{\omega_0}{v_\phi}\right)^2 + \left(\frac{\Delta\omega}{v_g}\right)^2\right)^{-1/2}$$

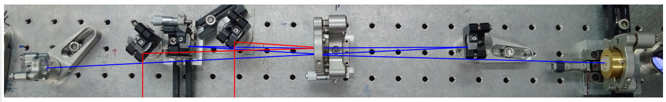
Beyond the Standard Quantum Limit

Further reduction of the minimum resolvable distance if the input beam has a mean field mode squeezed in the phase quadrature and a time-of-flight vacuum mode squeezed in the amplitude quadrature [4]



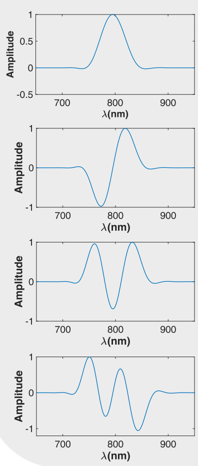
Experimental Setup





Our source consists in a synchronously pumped optical cavity resonant for the pump of a non-collinear type I parametric down-conversion process.
This kind of cavity provides a power enhancement of the whole frequency comb which resonates in it.
Due to its high peak power the resonating pulse is able to generate an EPR state which has a high multipartite entanglement between the frequency components of the signal and the idler pulses.
When the EPR is sent to a beamsplitter a multimode squeezed state is obtained and can be analyzed by homodyne detection with a properly shaped local oscillator.

Multimode Quantum State Characterization



It is always possible to find a basis that diagonalize the interaction Hamiltonian describing the evolution of the multimode squeezed state.
In this basis the quantum state is found to be a set of independently squeezed modes [1].
The spectral shape of these eigenmodes is found diagonalizing the phase matching matrix $\mathcal{L}_{mn}$ whose eigenvalues are proportional to the squeezing parameter related to the corresponding eigenmode.
The eigenmode basis is a set of Hermite-Gaussian polynomials.

$$\begin{pmatrix}\hat{A}_m\\ \hat{B}_m\end{pmatrix} = \begin{pmatrix}\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}}\\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\end{pmatrix}\begin{pmatrix}\hat{a}_m\\ \hat{b}_m\end{pmatrix}$$

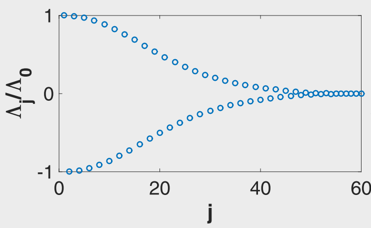
$$H = i\frac{\hbar}{2}k\left(\hat{A}^\dagger\right)^T \mathcal{L}\hat{A}^\dagger + \text{h.c.}$$

$$\mathcal{L}_{mn} = \text{sinc}\left[(k_{m+n}^{(p)} - k_m^{(s)} - k_n^{(i)})\frac{\ell}{2}\right]\alpha_{m+n}$$

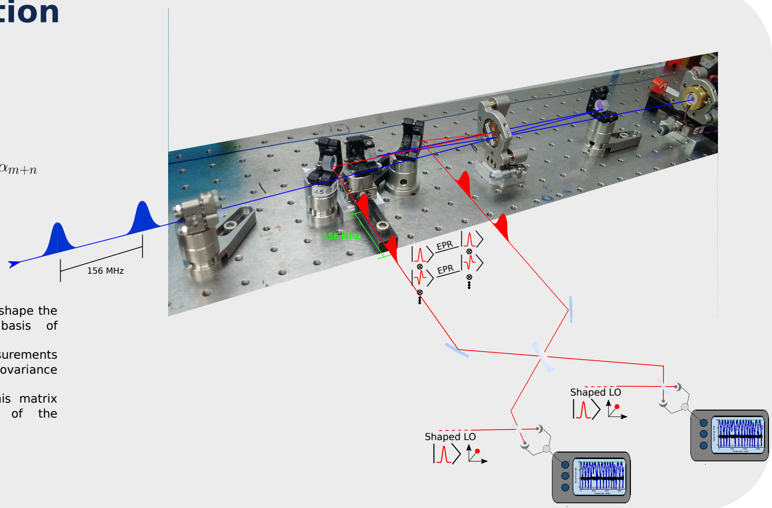
$$\mathcal{U}\mathcal{L}\mathcal{U}^T = \Lambda$$

$$\hat{S}^\dagger = \mathcal{U}\hat{A}^\dagger$$

$$\Rightarrow H = i\hbar\sum_i \Lambda_j\left(S_j^\dagger\right)^2 + \text{h.c.}$$



Via pulse-shaping we can shape the local oscillator in a basis of frequency pixels.
Different homodyne measurements then allow to built a covariance matrix.
The diagonalization of this matrix gives the eigenmodes of the quantum state.



References:

(1) J. Roslund, R. M. de Ara´ujo, S. Jiang, C. Fabre, and N. Treps, Nature Photonics, 8, 109112 (2014)
(2) R. Raussendorf, H. J. Briegel, Phys. Rev. Lett., 86(22), 5188, (2001)
(3) B. Lamine, C. Fabre, and N. Treps, Phys.Rev. Lett., 101, 123601 (2008)
(4) O. Pinel, J. Fade, D. Braun, P. Jian, N. Treps and C. Fabre, Phys. Rev. A, 85, 010101, (2011)