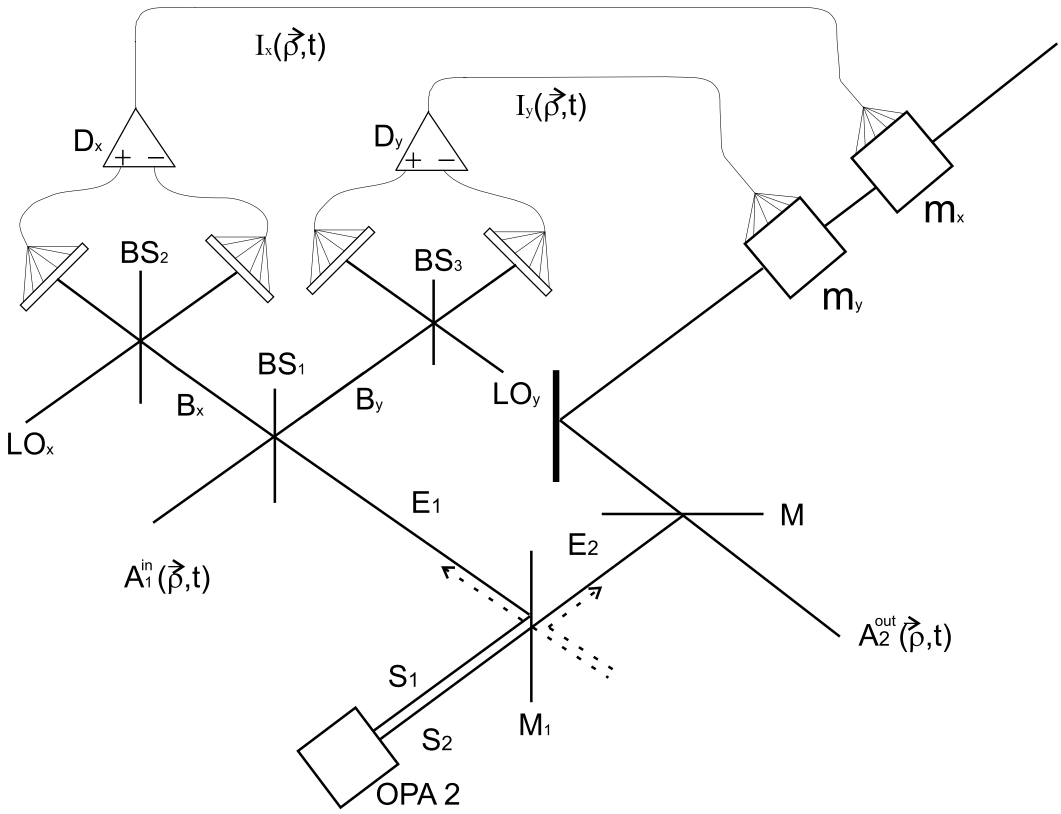
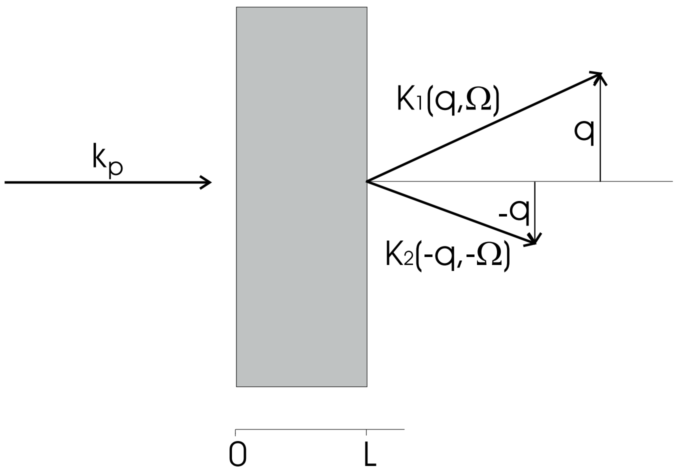
Scheme of teleportation



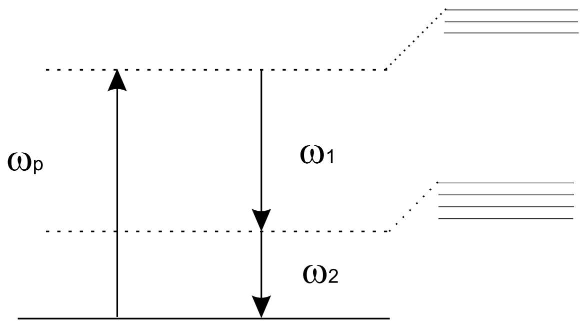
$S_{1,2}(\vec{\rho},t)$ - two broadband multimode squeezed beams, created by one nongenerate travelling-wave OPA,
$A_1^{in}(\vec{\rho},t)$ - input field, $A_2^{out}(\vec{\rho},t)$ - teleported field,
M_1 - mirror, transmitted the field $S_2(\vec{\rho},t)$ and reflected $S_1(\vec{\rho},t)$.
$D_{x,y}$ - photodetectors of the corresponding quadratures,
$m_{x,y}$ - modulators of the corresponding quadratures.

EPR fields

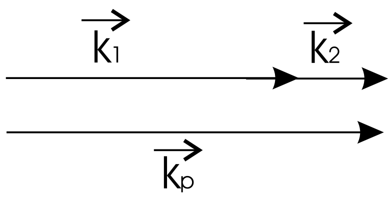
- Non-degenerate parametrical interaction (squeezing) inside a nonlinear crystal.



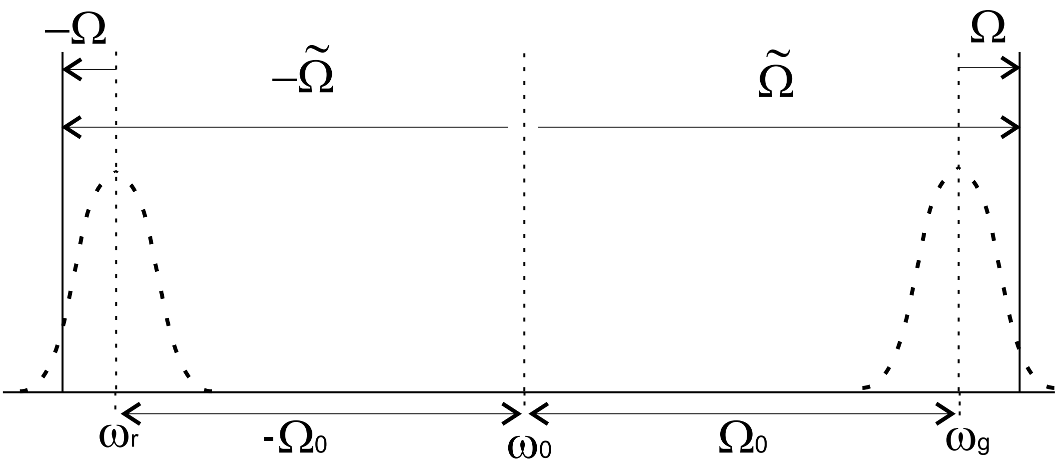
- Two photons appear with different frequencies, composition of last ones gives the frequency of pumping wave, $\omega_1 + \omega_2 = \omega_p$.



- Collinear non-degenerate matching

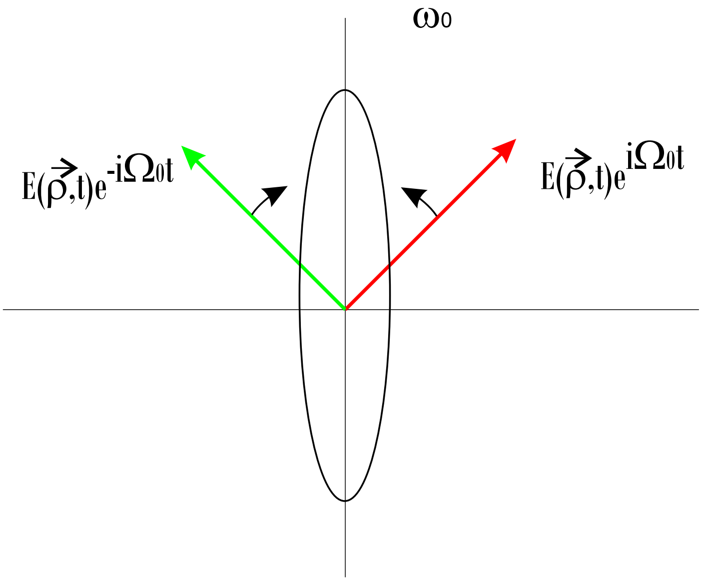


- Two EPR fields,



$$\omega_1 = \omega_0 + \Omega_0, \qquad \omega_2 = \omega_0 - \Omega_0$$

- Formation of the squeezing ellipse



Two vectors of EPR fields rotate in the complex plane towards each other composing an ellipse of squeezing.

Transformation of squeezing

- The transformation of squeezing for the Fourier-amplitudes

$$\hat{e}_1(\vec{q},\Omega) = U_1(\vec{q},\Omega)\hat{a}_1(\vec{q},\Omega) + V_1(\vec{q},\Omega)\hat{a}_2^+(-\vec{q},-\Omega),$$
$$\hat{e}_2(\vec{q},\Omega) = U_2(\vec{q},\Omega)\hat{a}_2(\vec{q},\Omega) + V_2(\vec{q},\Omega)\hat{a}_1^+(-\vec{q},-\Omega),$$

here $a_n(\vec{q},\Omega)$, $n = 1, 2$ are two field operators in the vacuum state.

- The coefficients $U_n(\vec{q},\Omega)$ and $V_n(\vec{q},\Omega)$ depend on the pump-field amplitude of the OPAs. For the type-I travelling-wave OPAs:

$$U(\vec{q},\Omega) = e^{i[(k_z(\vec{q},\Omega)-k)l-\delta(\vec{q},\Omega)/2]}\left\{\cosh[\Gamma(\vec{q},\Omega)] + i\frac{\delta(\vec{q},\Omega)}{2\Gamma(\vec{q},\Omega)}\sinh[\Gamma(\vec{q},\Omega)]\right\},$$
$$V(\vec{q},\Omega) = e^{i[(k_z(\vec{q},\Omega)-k)l-\delta(\vec{q},\Omega)/2]}\frac{\sigma}{\Gamma(\vec{q},\Omega)}\sinh[\Gamma(\vec{q},\Omega)],$$

here l is the length of the nonlinear crystal, $k_z(\vec{q},\Omega)$ is the longitudinal component of the wave vector $\vec{k}(\vec{q},\Omega)$.
The parameter $\Gamma(\vec{q},\Omega)$:

$$\Gamma(\vec{q},\Omega) = \sqrt{\sigma^2 - \frac{\delta^2(\vec{q},\Omega)}{4}},$$

where σ is the dimensionless coupling strength of nonlinear interaction, taken as real for simplicity.

- The dimensionless mismatch function

$$\delta(\vec{q},\Omega) = \delta_0 + \tau_{coh}\Omega + \frac{1}{2}\epsilon(\tau_{coh}\Omega)^2 - \frac{q^2}{q_0^2},$$

where

$$\delta_0 = (k_1 + k_2 - k_p)l$$

is the collinear phase-mismatch,

$$q_0 = \sqrt{\frac{4\pi}{l}\frac{n_1 n_2}{(n_1\lambda_2 + n_2\lambda_1)}},$$

this parameter defines the typical bandwidth of phase matching,

$$\tau_{coh} = \mid \frac{l}{\upsilon_g^1} - \frac{l}{\upsilon_g^2} \mid$$

is the coherence time and

$$\epsilon = \left(\frac{d^2 k_1}{d\Omega^2} + \frac{d^2 k_2}{d\Omega^2} \right) \frac{l}{\tau_{coh}^2}$$

is a dimensionless parameter.

• For the $\lambda_1 = 1.062nm$ and $\lambda_2 = 0.5321nm$ numerical computations gave the following results: $\tau_{coh} = 3.25{\cdot}10^{-13}\ \ s$, $\epsilon = 0.0035$, $q_0 = 0.081\ \ nm^{-1}$, $l_{coh} = 12.37\ \ nm$.

• The degree of EPR correlation is determined by the orientation angle $\psi(\vec{q}, \Omega)$ of the major axis of the squeezing ellipse [4],

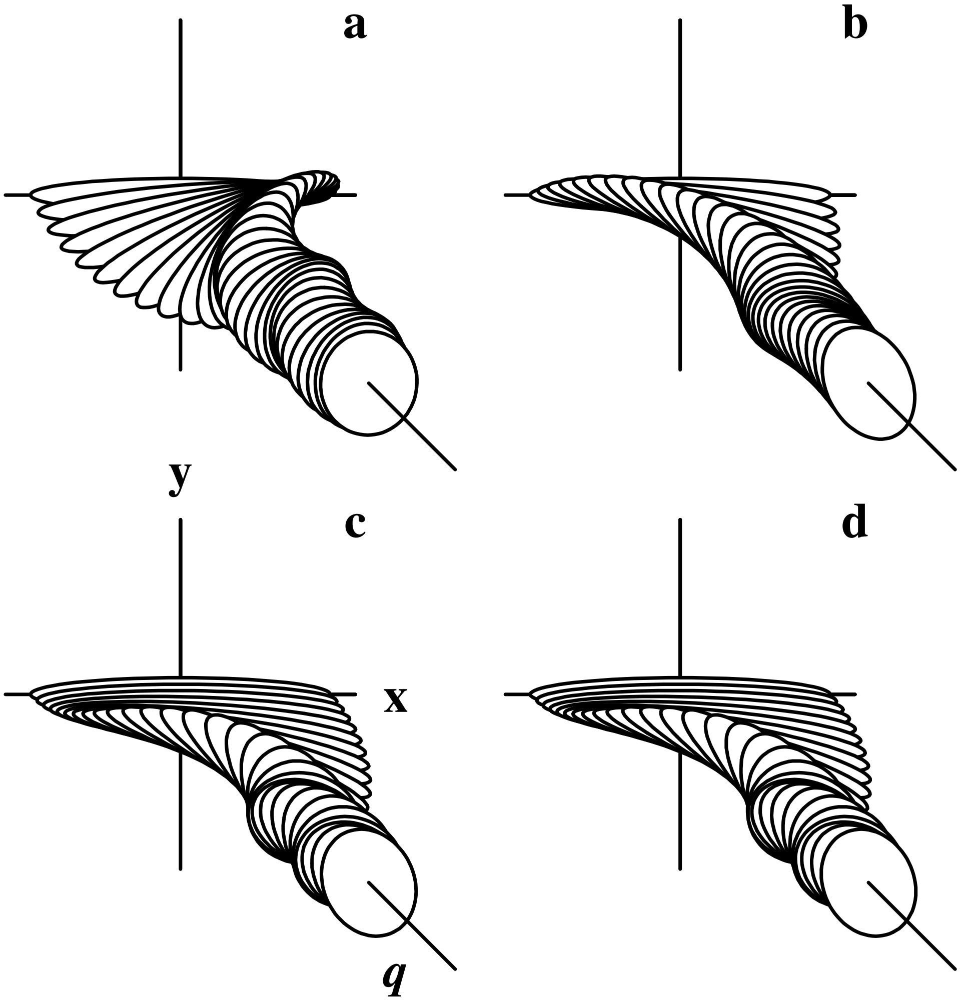
$$\psi_1(\vec{q}, \Omega) = \psi_2(-\vec{q}, -\Omega) = \frac{1}{2} arg(U_1(\vec{q}, \Omega) V_2(-\vec{q}, -\Omega)),$$

and by the degree of squeezing $r(\vec{q}, \Omega)$,

$$e^{\pm r_1(\vec{q}, \Omega)} = e^{\pm r_2(-\vec{q}, -\Omega)} = |U_1(\vec{q}, \Omega)| \pm |V_2(-\vec{q}, -\Omega)|.$$

• The spatio-temporal parameters of squeezing and entanglement are sensitive to the rotation of the squeezing ellipses in the (x, y) plane of complex amplitude with frequencies $\vec{q}, \Omega$.

Squeezing ellipses for different $\vec{q}, \Omega$



Here we present the squeezing ellipses for the broadband in space and time fields $E_1(\vec{\rho}, t)$ (a) and $E_2(\vec{\rho}, t)$ (b) in dependence of the mismatch $\delta(\vec{q}, \Omega)$ (arbitrary units). The rotations (a) and (b) are in dependence of the temporal frequency Ω and (c) and (d) in dependence of the spatial frequency q. As a result of the rotation, the noise suppression in the given field quadrature goes over to the noise amplification at higher frequencies. This rotation in dependence of the spatial frequency can be effectively eliminated by a properly inserted lens.

Quantum statistics of the teleported field

• Teleported field

$$A_1^{out}(\vec{\rho}, t) = A_2^{in}(\vec{\rho}, t) + F(\vec{\rho}, t),$$

where

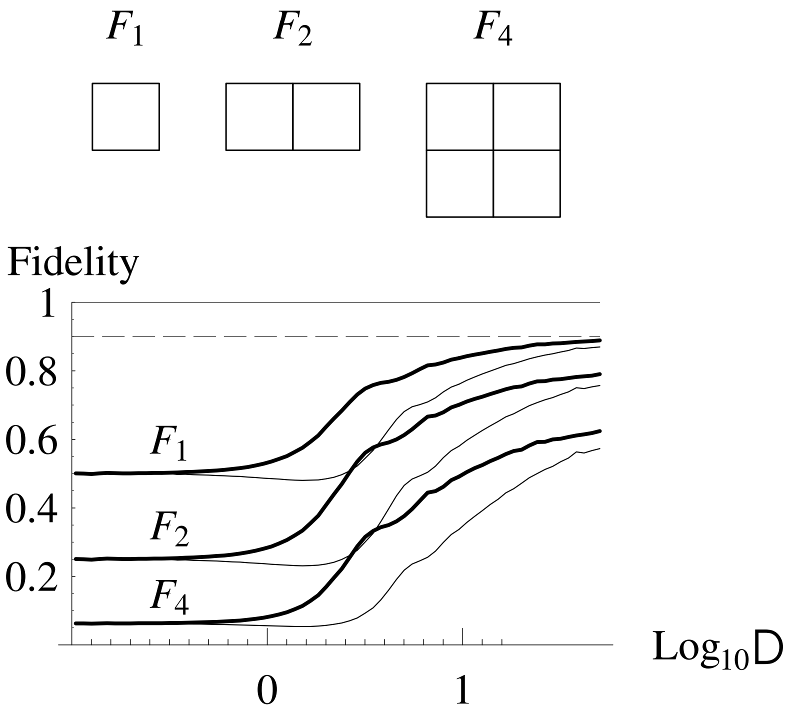
$$F(\vec{\rho}, t) = E_1(\vec{\rho}, t) + E_2^{+}(\vec{\rho}, t)$$

is noise field added by the teleportation process.

• The quality of reconstruction of the quantum state $\mid \psi_{in} >$ of the input field in the teleportation process is quantified via the fidelity parameter F.

$$F = \mid < \psi_{in} \mid \psi_{out} > \mid^2$$

• In [2] it was shown the reduced fidelity dependence on the pixel size and on the number of pixels



The wide and narrow solid lines correspond to the observation with (wide lines) and without (narrow lines) diffraction phase shift compensation with the use of a lens arrangement.

References

[1] A. Furusawa et al, Science, 282, 706 (1998) ; W. P. Bowen et al, Phys. Rev. A 67, 032302 (2003).
[2] I. V. Sokolov, M. I. Kolobov, A. Gatti, L. A. Lugiato, Opt. Comm., 193, 175 (2001).
[3] J. Huang and P. Kumar, Phys. Rev. Lett., 68, 2153 (1992).
[4] A. Gatti, I. V. Sokolov, M. I. Kolobov, and L. A. Lugiato, Eur. Phys. J. D 30, 123 (2004).