Quantum Nonlinear Optical Pulse Propagation

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[Outline]

1. How quantum solitons are formed?
2. How quantum soliton squeezing is produced?
3. How quantum soliton entanglement is produced?
4. Different types of quantum solitons.

How classical solitons are formed?

Nonlinear Schroedinger equation (NLSE):

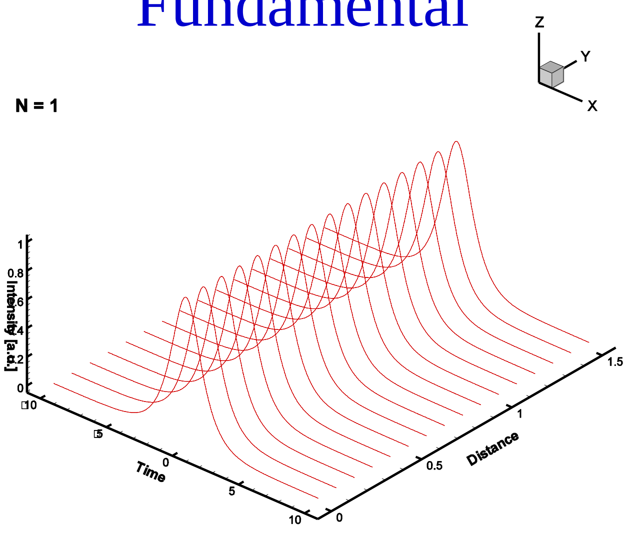
$$i\frac{\partial}{\partial z}U(z,t) = -\frac{1}{2}\frac{\partial^2}{\partial t^2}U(z,t) - |U(z,t)|^2\, U(z,t)$$

A. Hasegawa and F. Tappert, Appl. Phys. Lett. Vol. 23, Issue 3, pp. 142-144, (1973).

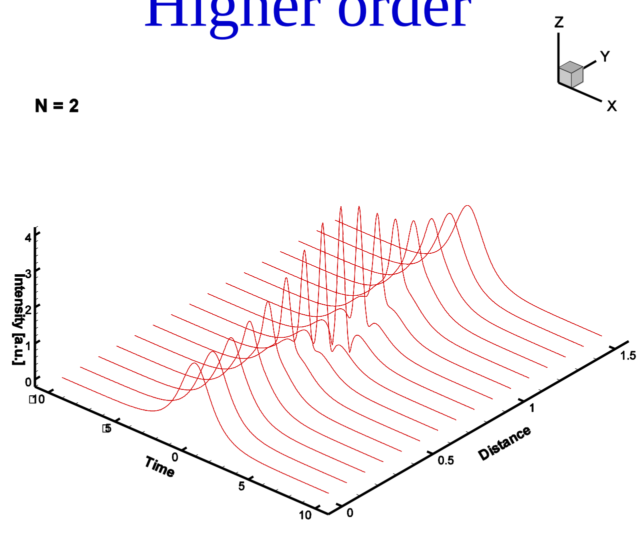
Fundamental solitons:

$$U(z,t) = \frac{n_0}{2}\exp[i\frac{n_0^2}{8}z + i\theta_0]\operatorname{sech}[\frac{n_0}{2}t]$$

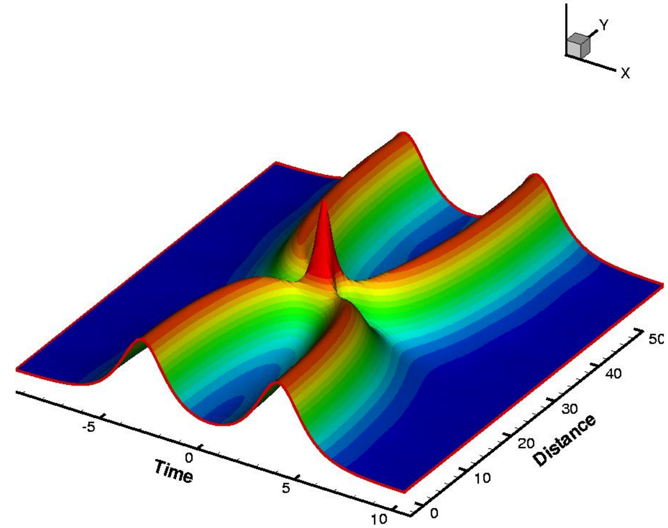
Fundamental



Higher order



Soliton interaction



Quantum description of optical pulses

$$\hat{a}(\tau) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \hat{a}(\Delta\omega)\, e^{-i\,\Delta\omega\,\tau}\, d\,\Delta\omega$$

$$|\,\Psi(z)\rangle = \sum_{n=0}^{\infty} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} f_n(z, \tau_1, \cdots, \tau_n)\, \hat{a}^{\dagger}(\tau_1) \cdots \hat{a}^{\dagger}(\tau_n)\, d\,\tau_1 \cdots d\,\tau_n \Big|\, 0 \Big\rangle$$

Quantum Nonlinear Schrodinger Equation

$$\frac{\partial}{\partial z}\, \hat{a}(z, \tau) = i\, \frac{1}{2}\, \frac{\partial^2}{\partial \tau^2}\, \hat{a}(z, \tau) + i\, \hat{a}^{\dagger}(z, \tau)\, \hat{a}(z, \tau)\, \hat{a}(z, \tau)$$

$$\frac{\partial}{\partial z}\, f_n(z, \tau_1, \cdots, \tau_n) = i \left(\frac{1}{2} \sum_{j=1}^{n} \frac{\partial^2}{\partial {\tau_j}^2} + \sum_{1 \le j < k \le n} \delta(\tau_j - \tau_k) \right) f_n(z, \tau_1, \cdots, \tau_n)$$

Bethe's ansatz method

Microscopic quantum state solution

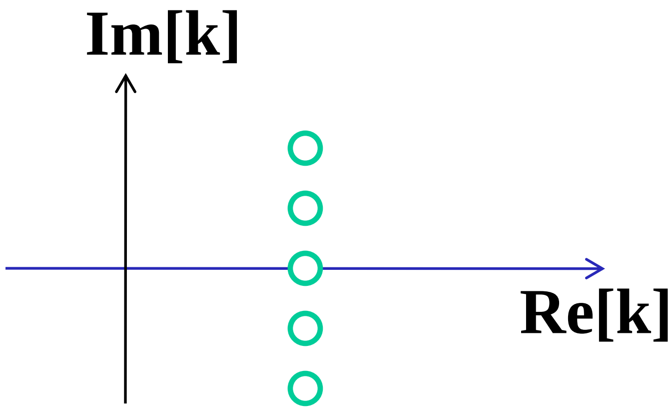
For $\tau_1 < \tau_2 < \ldots\ldots < \tau_n$

No nonlinearity: $f_n(z, \tau_1, \cdots, \tau_n) \propto e^{i k_1 \tau_1 + i k_2 \tau_2 + \ldots + i k_n \tau_n}$

With nonlinearity:

$$f_n(z, \tau_1, \cdots, \tau_n) = A_{\{1,2,3,..n\}}\, e^{i k_1 \tau_1 + i k_2 \tau_2 + \ldots + i k_n \tau_n} + A_{\{2,1,3,..n\}}\, e^{i k_2 \tau_1 + i k_1 \tau_2 + \ldots + i k_n \tau_n} + \text{other permutations}$$

$$A_{\{2,1,3,..n\}} = \frac{k_2 - k_1 - i}{k_2 - k_1 + i} A_{\{1,2,3,..n\}}$$



Bound eigenstates:

If $k_j = p - \frac{i}{2}(n - 2j + 1)$

then only the first term is non-zero.

How quantum solitons are formed?

Bound eigenstates

$$|\, n,\, p,\, z\rangle = N_c \,\mathrm{Exp}[-i\, K(n,\, p)\, z] \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \mathrm{Exp}\left[i\, p \sum_{k=1}^{n} \tau_k - \frac{1}{2} \sum_{1 \le i < j \le n} \left| \tau_j - \tau_i \right| \right] d\,\tau_1 \cdots d\,\tau_n \Big| 0 \Big\rangle$$

$$K(n,\, p) = \frac{1}{2}\, n\, p^2 - \frac{1}{24}\, n\left(n^2 - 1\right)$$

Soliton pulses

$$|\, \Psi(z)\rangle = \sum_n \int g_n(p) \Big| n,\, p,\, z \Big\rangle\, d\, p$$

$$\theta(n,\, p) = \{K(n+1,\, p) - K(n,\, p)\}\, z \approx \frac{z}{2}\, p^2 - \frac{z}{8}\, n^2$$

$$\frac{\partial}{\partial p} \{K(n+1,\, p) - K(n,\, p)\} = p$$

Quantum soliton pulses are changing:
phase spreading and position spreading effects

Y. Lai and H.A. Haus, PRA 40, p.854, 1989.

Quantum soliton perturbation theory

NLSE

$$i\frac{\partial}{\partial z}U(z,t) = -\frac{1}{2}\frac{\partial^2}{\partial t^2}U(z,t) - |U(z,t)|^2 U(z,t)$$

Soliton pulses

$$U(z,t) = \frac{n_0}{2}\exp\left[ip_0 t + i\frac{n_0^2}{8}z - i\frac{p_0^2}{2}z + i\theta_0\right]\mathrm{sech}\left[\frac{n_0}{2}(t - T_0 - p_0 z)\right]$$

Phase spreading

$$\Delta\hat{n}(z) = \Delta\hat{n}(0)$$

$$\Delta\hat{\theta}(z) = \Delta\hat{\theta}(0) + \frac{n_0}{4}z\Delta\hat{n}(0)$$

Assuming $p_0 = 0$

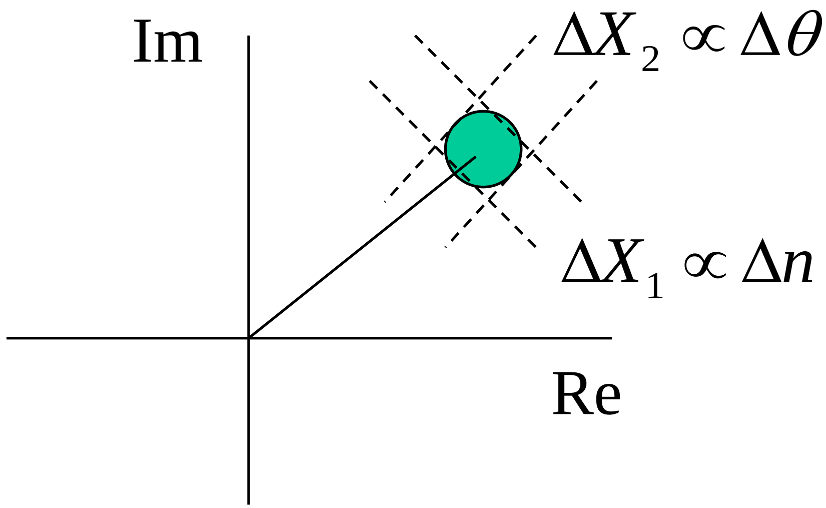
Position spreading

$$\Delta\hat{p}(z) = \Delta\hat{p}(0)$$

$$\Delta\hat{T}(z) = \Delta\hat{T}(0) + z\Delta\hat{p}(0)$$

H.A. Haus and Y. Lai, J. Opt. Soc. Am. B **7**, 386(1990)

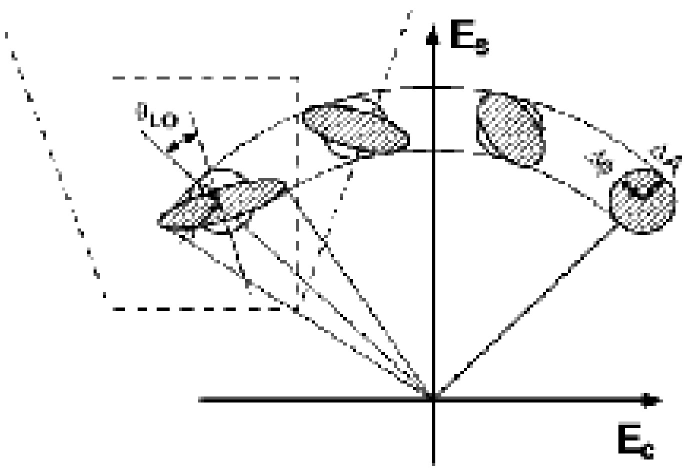
Phase spreading and quadrature squeezing



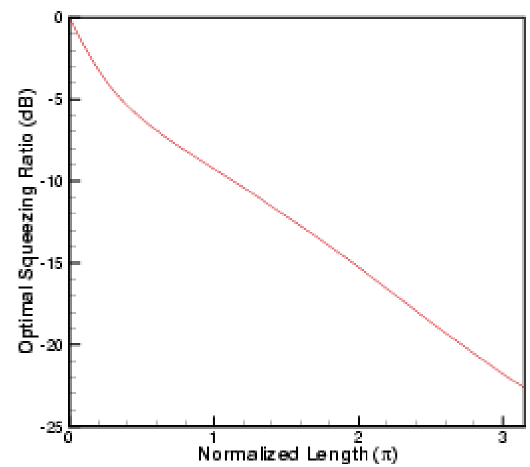
$$\Delta\hat{n}(z) = \Delta\hat{n}(0)$$

$$\Delta\hat{\theta}(z) = \Delta\hat{\theta}(0) + \frac{n_0}{4} z \Delta\hat{n}(0)$$

$$\Delta\hat{X}_\theta(z) = \alpha_1 \Delta\hat{n}(z) + \alpha_2 \Delta\hat{\theta}(z)$$



$$R = \min \frac{Var[\Delta\hat{X}_\theta(z)]}{Var[\Delta\hat{X}_\theta(0)]}$$



How to detect?

$$\hat{u}(z,t) = \Delta\hat{n}(z)u_n(t) + \Delta\hat{\theta}(z)u_\theta(t) + \Delta\hat{p}(z)u_p(t) + \Delta\hat{T}(z)u_T(t) + continuum$$

Projection

$$\Delta\hat{n}(z) = \left\langle f_n(t) \,|\, \hat{u}(z,t) \right\rangle$$

$$\Delta\hat{\theta}(z) = \left\langle f_\theta(t) \,|\, \hat{u}(z,t) \right\rangle$$

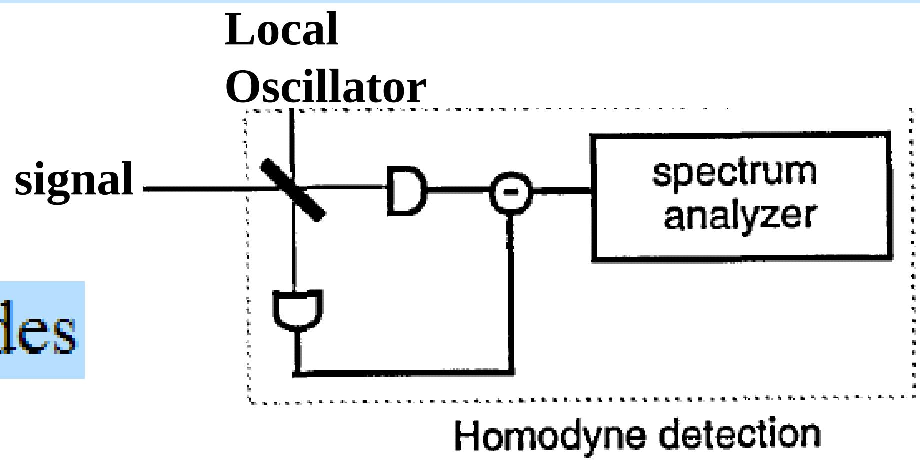
$$\Delta\hat{p}(z) = \left\langle f_p(t) \,|\, \hat{u}(z,t) \right\rangle$$

$$\Delta\hat{T}(z) = \left\langle f_T(t) \,|\, \hat{u}(z,t) \right\rangle$$

Optically, such projection can be implemented by homodyne detection.

Projection interpretation of homodyne detection

$$\hat{M}(z) = \;< f_{\mathrm{LO}}(t) \,\Big|\, \hat{u}(z,t) >= \int \frac{1}{2}[\, f_{\mathrm{LO}}{}^{*}(t)\, \hat{u}(z,t) + h.c.]\, \mathrm{dt}$$



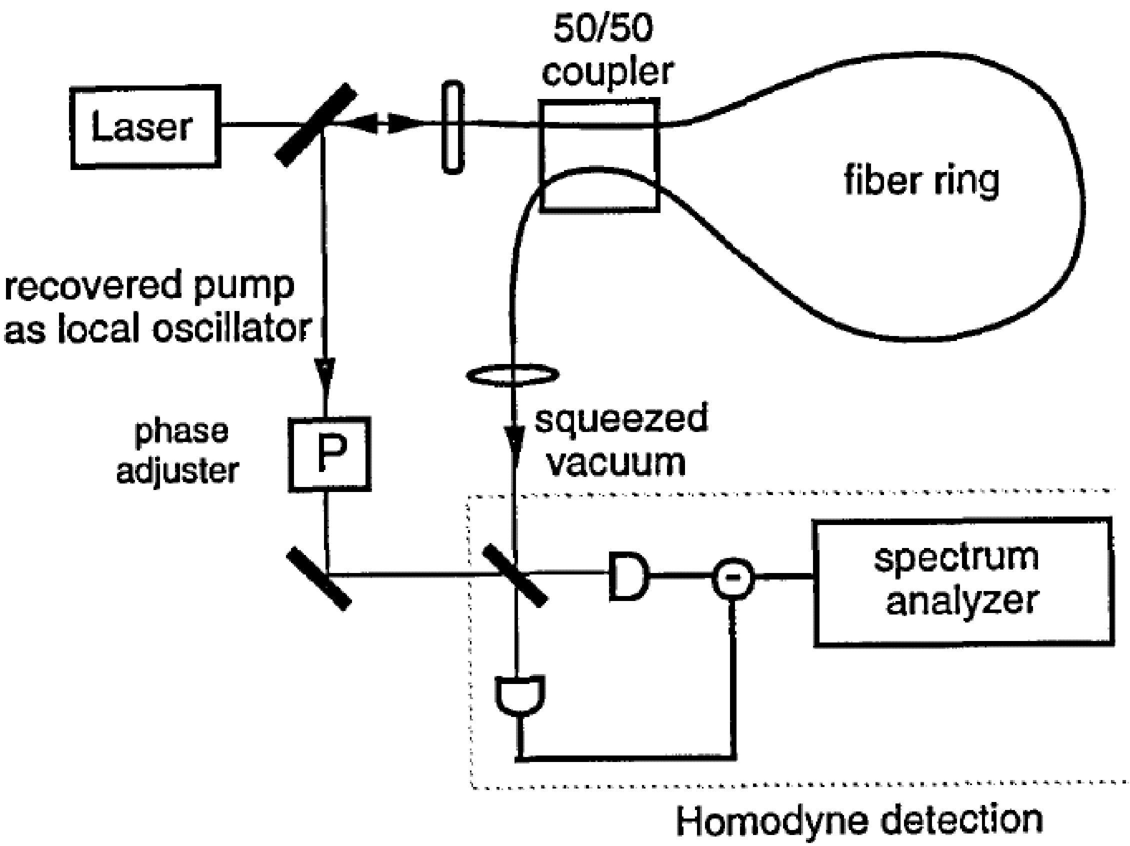
$$\hat{u}(t) = \hat{a}\, u_m(t) + \text{other modes}$$

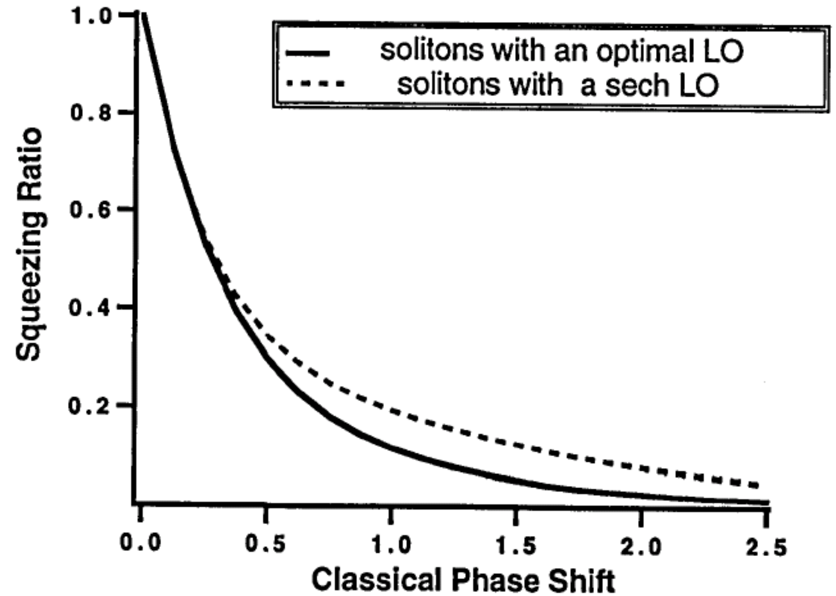
$$\hat{a} = \hat{q} + i\,\hat{p}$$

$$\hat{q} = \langle u_m(t) \mid \hat{u}(t)\rangle = \frac{1}{2}\int \left[u_m{}^{*}(t)\,\hat{u}(t) + u_m(t)\,\hat{u}^{\dagger}(t)\right] d\,t$$

$$\hat{p} = \langle i\, u_m(t) \mid \hat{u}(t)\rangle = \frac{i}{2}\int \left[-u_m{}^{*}(t)\,\hat{u}(t) + u_m(t)\,\hat{u}^{\dagger}(t)\right] d\,t$$

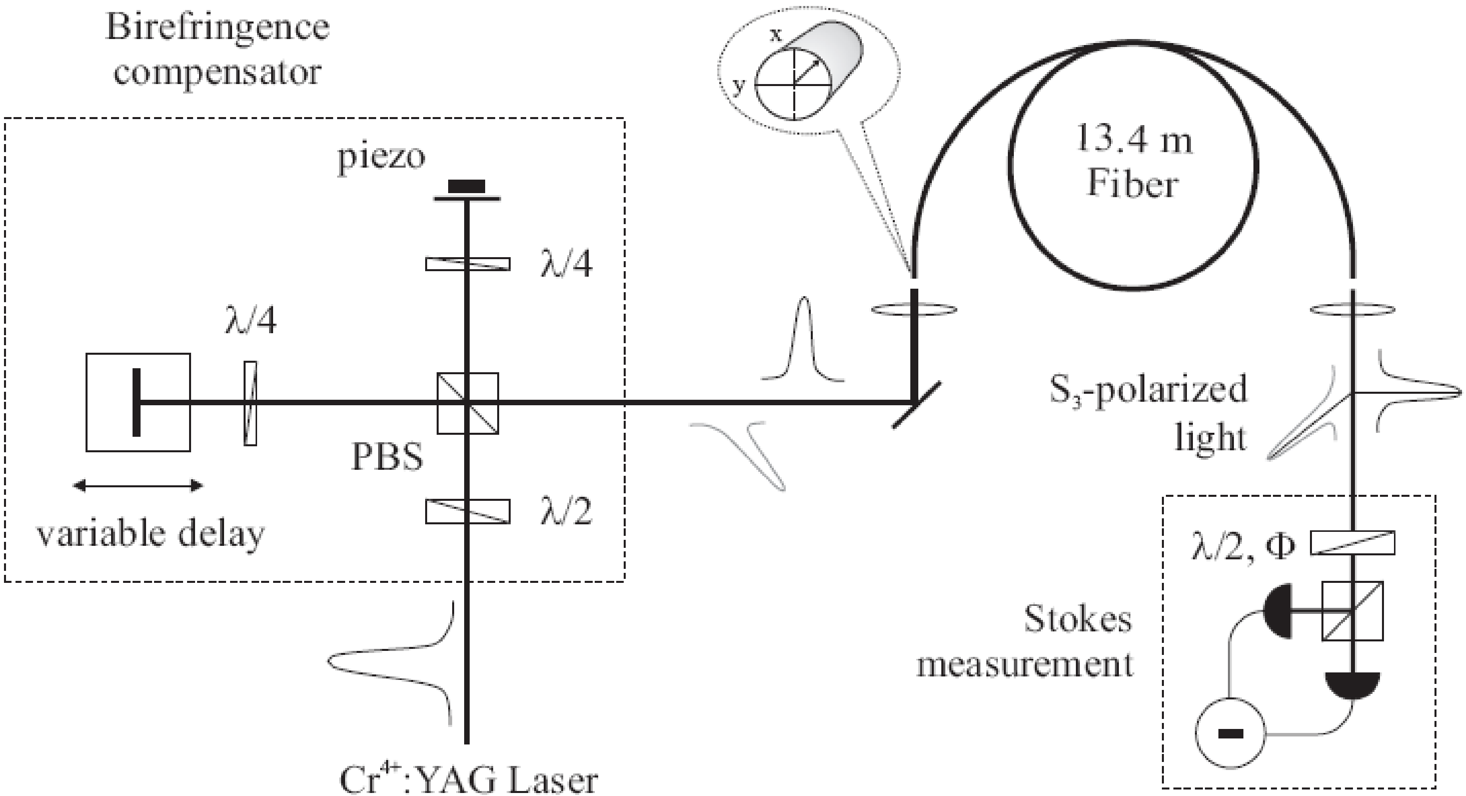
Squeezed vacuum state generation and detection





First Experiment: M. Rosenbluh and R. M. Shelby, Phys. Rev. Lett. 66, 153(1991).

Polarization squeezing



$$\begin{aligned} I &= |E_x|^2 + |E_y|^2, \\ Q &= |E_x|^2 - |E_y|^2, \\ U &= 2\mathrm{Re}(E_x E_y^*), \\ V &= 2\mathrm{Im}(E_x E_y^*), \end{aligned}$$

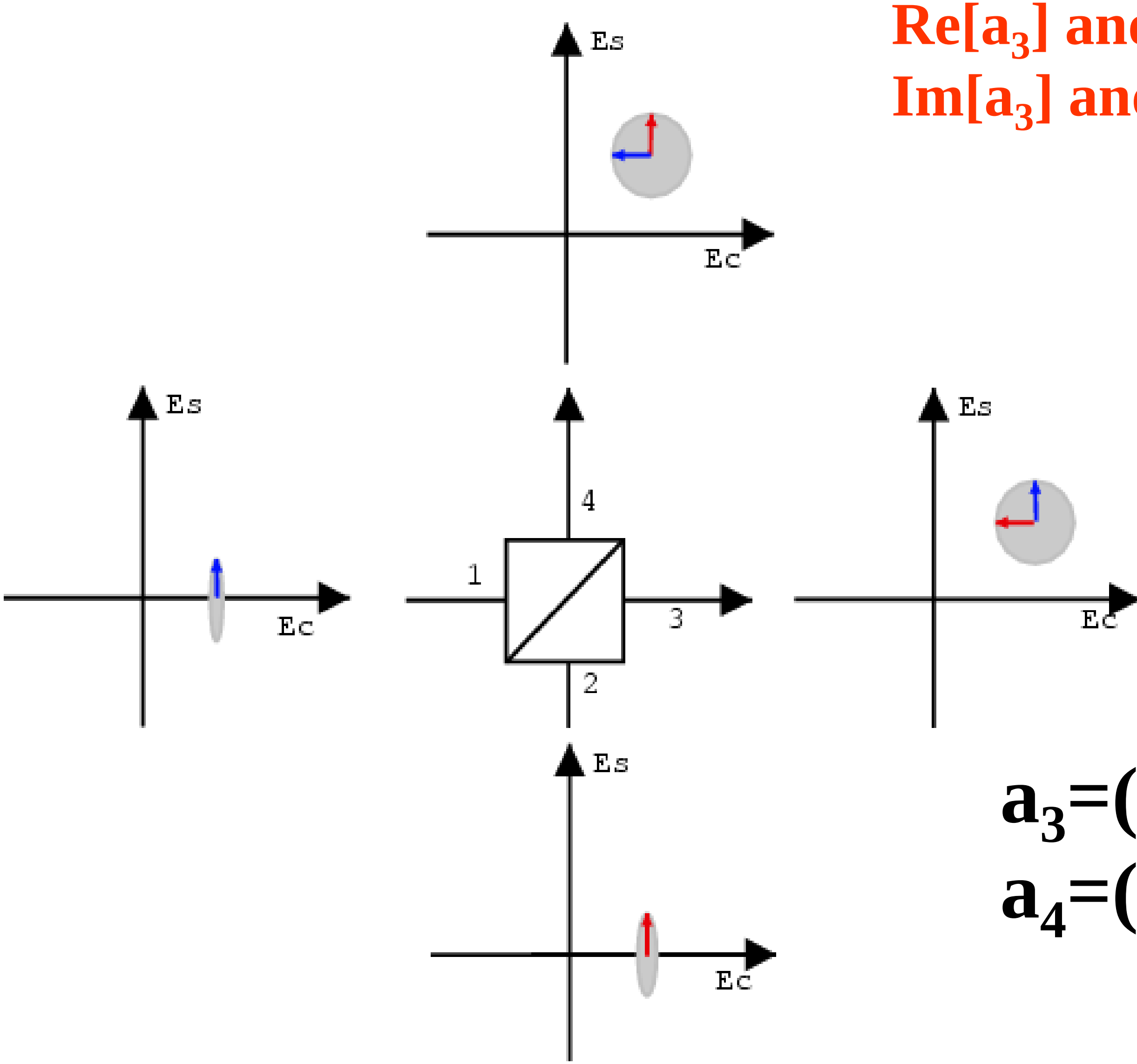
$$\hat{S}_\theta = \cos(\theta)\,\hat{S}_1 + \sin(\theta)\,\hat{S}_2$$

Observed noise reduction of -6.8±0.3 dB

1. J. F. Corney, P. Drummond, J. Heersink, V. Josse, G. Leuchs, and U.L. Andersen, Phys. Rev. Lett. 97, 023606 (2006).
2. R.-F. Dong, J. Heersink, J. F. Corney, P. D. Drummond, U. L. Andersen, and G. Leuchs, Opt. Lett. 33, 116 (2008).

Generation of EPR entangled beams with two independent squeezed states

Re[a_3] and Im[a_4] are correlated
Im[a_3] and Re[a_4] are correlated



a_3=(a_1 + i a_2)/2^0.5
a_4=(i a_1 + a_2)/2^0.5

Teleportation of Continuous Quantum Variables

Samuel L. Braunstein
SEECS, University of Wales, Bangor LL57 1UT, United Kingdom

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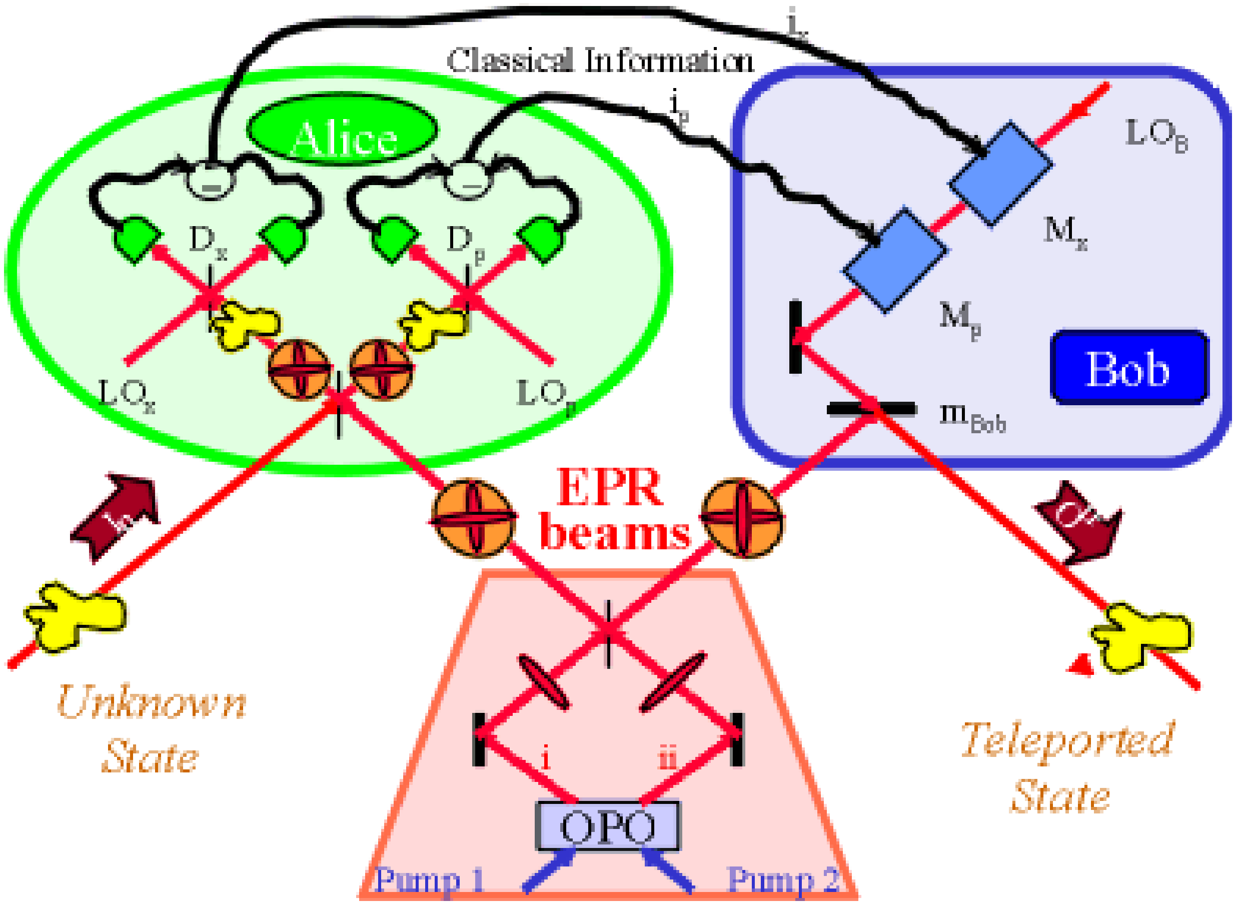
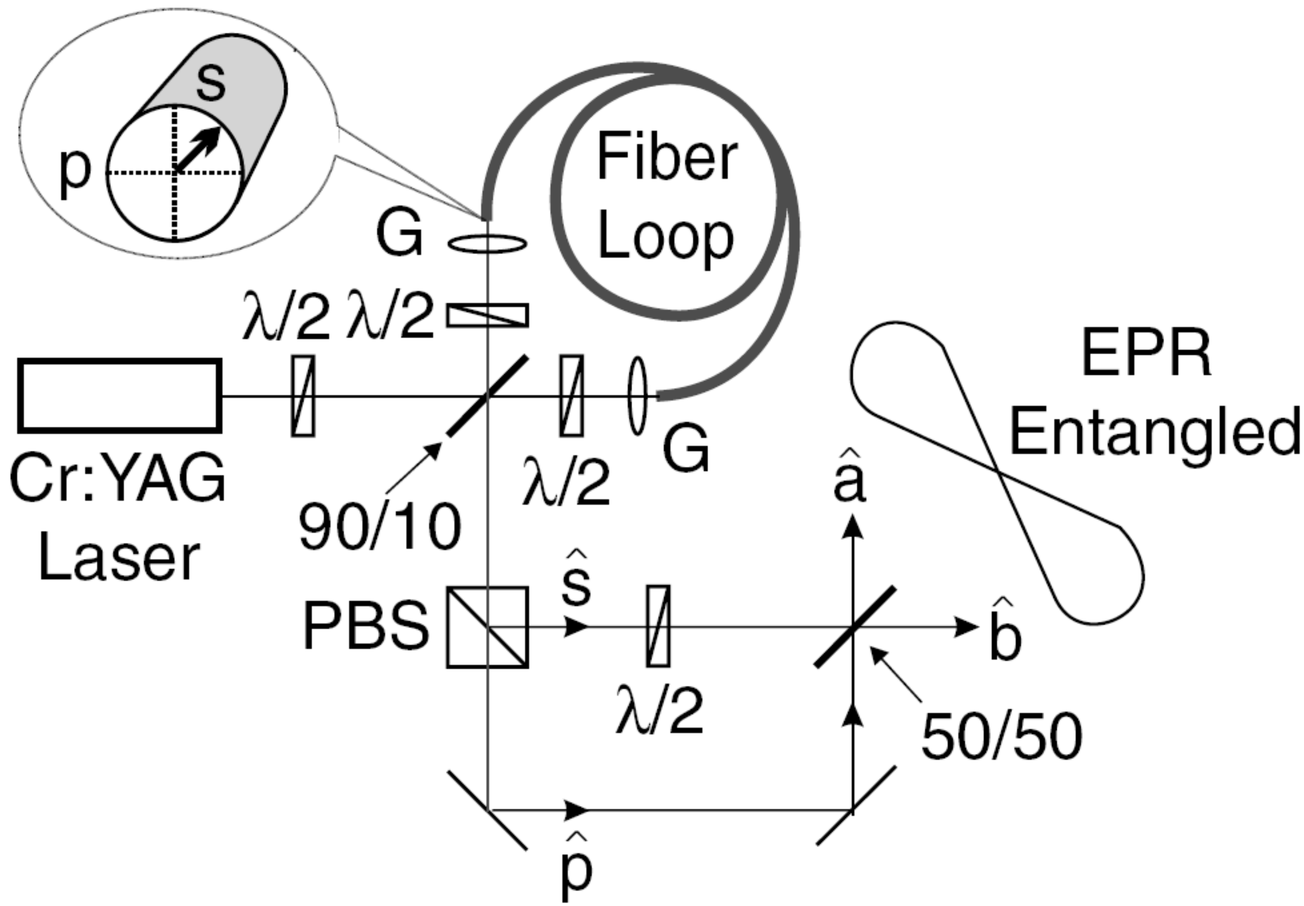
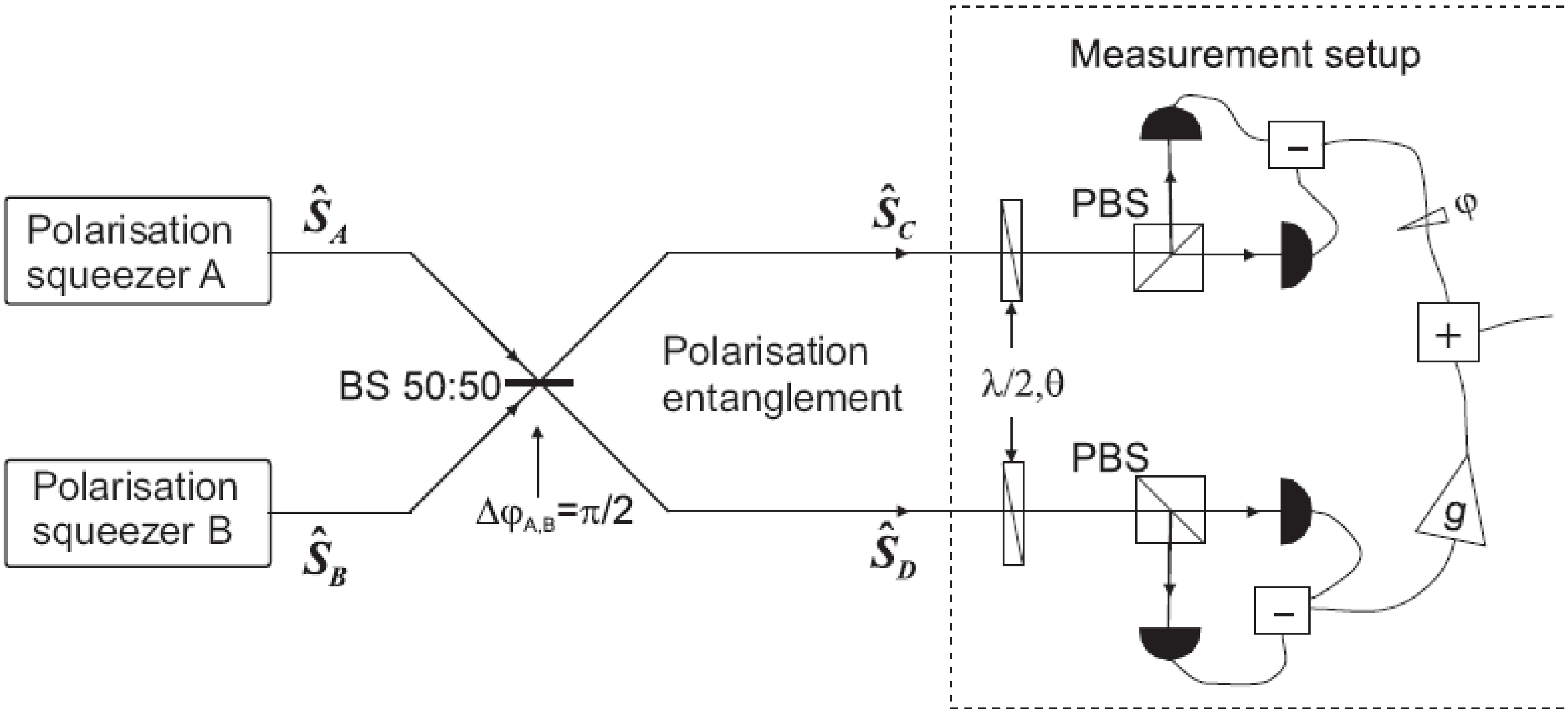


Generation of Continuous Variable Einstein-Podolsky-Rosen Entanglement via the Kerr Nonlinearity in an Optical Fiber

Ch. Silberhorn,[1] P. K. Lam,[1,2] O. Weiß,[1] F. König,[1] N. Korolkova,[1] and G. Leuchs[1]
[1]Zentrum für Moderne Optik, Universität Erlangen–Nürnberg, Staudtstraße 7/B2, D-91058 Erlangen, Germany
[2]Department of Physics, Faculty of Science, The Australian National University, ACT 0200, Canberra, Australia



Polarization entanglement states



The quantum correlations along the squeezed and the anti–squeezed Stokes parameters were observed to be -4.1±0.3 dB and -2.6±0.3 dB below the shot noise level respectively

R.-F. Dong, J. Heersink, J. Yoshikawa, O. Glöckl, U. L. Andersen, and G. Leuchs, New J. Phys. 9 410 (2007).

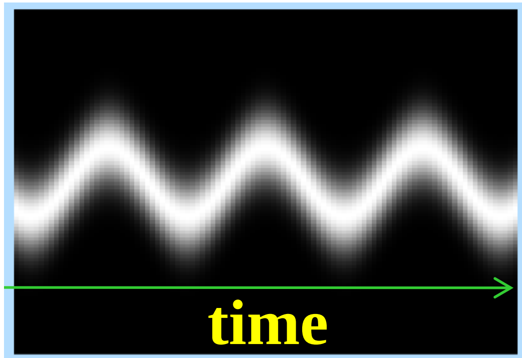
What if ………..

1. **Non-soliton cases?**
2. **With loss?**
3. **With higher order dispersion?**
4. **With self-Raman?**
5. **Different local oscillators?**

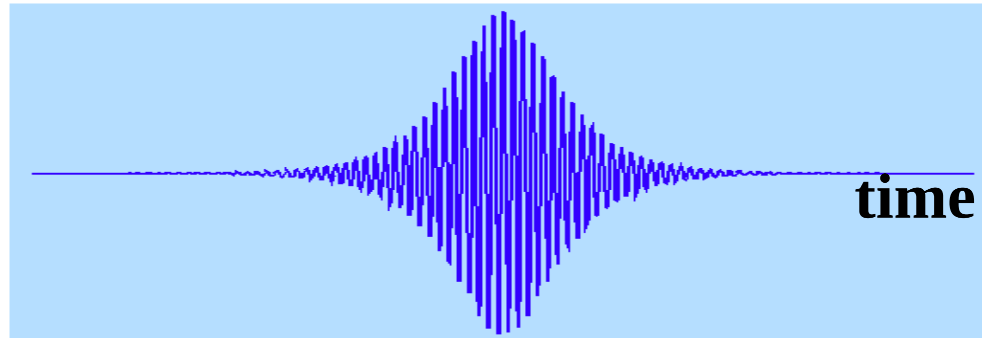
General numerical methods for quantum nonlinear optical pulse propagation

Quantum effects of optical pulses

Single light mode

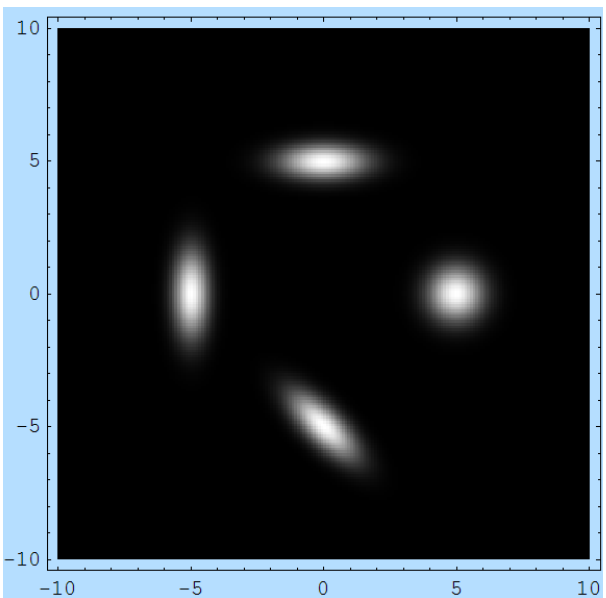


Optical pulse (multi-mode)



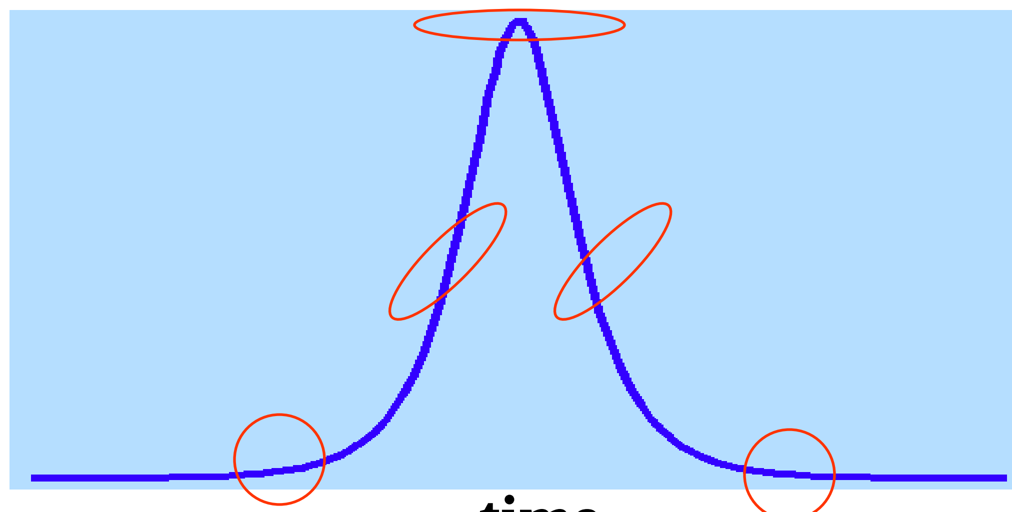
Phasor diagram of single mode

Re



Im

Time-sliced phasor diagram



time

Backpropagation method

$$\frac{\partial}{\partial z}\hat{U} = F(\hat{U}, \hat{U}^{\dagger})$$

$$\frac{\partial}{\partial z}\hat{u} = \mathrm{P}\bullet\hat{u}$$

$$\frac{\partial}{\partial z}u^A = P^A\bullet u^A$$

$$\frac{\partial}{\partial z}\langle u^A | u\rangle = 0$$

$$\hat{M}(z) = \langle u^A(z,t) | u(z,t)\rangle = \langle u^A(0,t) | u(0,t)\rangle$$

$$\mathrm{Var}[\hat{M}(z)] = \frac{1}{4}\int |u^A(0,t)|^2\, dt$$

Linearization approximation

Relate the output operators to the input operators.

1. Quantum correlation also can be calculated.
2. Additional noise terms also can be included.

Y. Lai and S.-S. Yu, PRA 51, p.817, 1995.

Quantum noise calculation

$$\frac{\partial}{\partial z}\hat{U} = F(\hat{U}, \hat{U}^\dagger)$$

$$\frac{\partial}{\partial z}\hat{u} = \mathrm{P} \bullet \hat{u}$$

$$\frac{\partial}{\partial z}u^A = P^A \bullet u^A$$

$$\frac{\partial}{\partial z}\langle u^A \mid u \rangle = 0$$

$$\hat{M}(z) = \langle u^A(z,t) \mid u(z,t) \rangle = \langle u^A(0,t) \mid u(0,t) \rangle$$

$$\mathrm{Var}[\hat{M}(z)] = \frac{1}{4}\int |u^A(0,t)|^2 \, dt$$

Linearization approximation

Relate the output operators to the input operators.

1. Quantum correlation also can be calculated.

2. Additional noise terms also can be included.

Y. Lai and S.-S. Yu, PRA 51, p.817, 1995.

Optimized projection function

$$u^A(z,t) = f_L(t)$$

$$u^A(0,t) = A_{0\leftarrow z} \bullet f_L(t)$$

$$\hat{u}(z,t) = L_{z\leftarrow 0} \bullet \hat{u}(0,t)$$

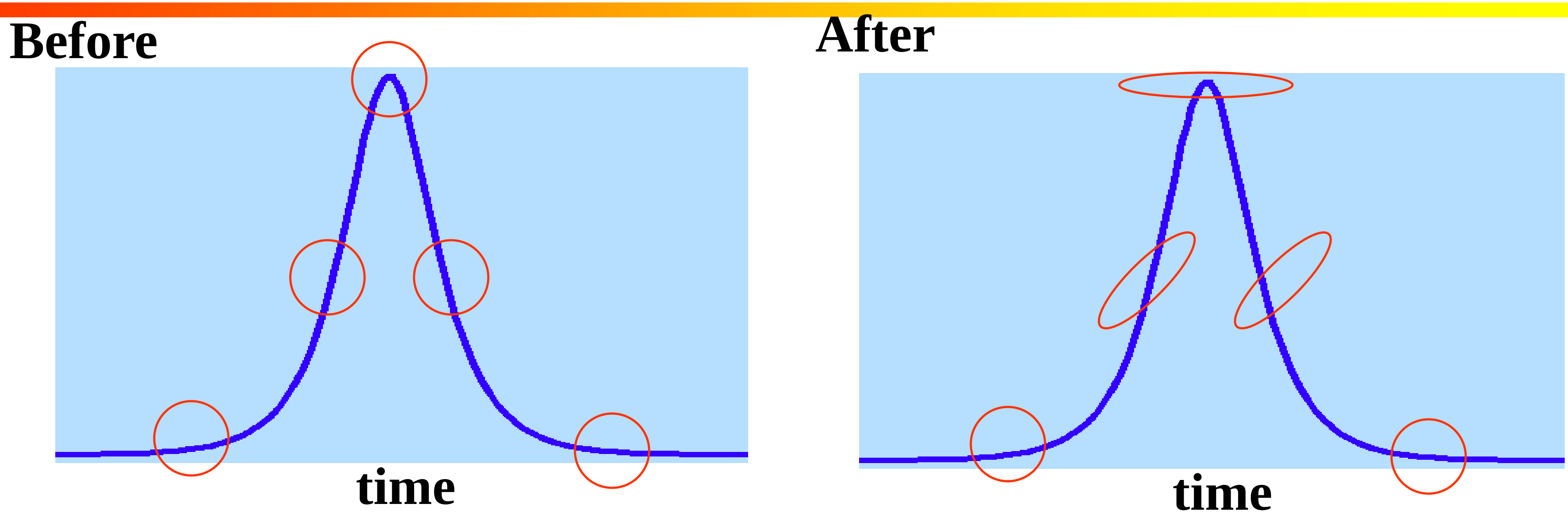
$$R = \frac{\mathrm{Var}\left[\hat{M}(L)\right]}{\mathrm{Var}\left[\hat{M}(0)\right]} = \frac{\mathrm{Var}[\langle f_L(t) \mid \hat{u}(z,t)\rangle]}{\mathrm{Var}[\langle f_L(t)) \mid \hat{u}(0,t)\rangle]} = \frac{\langle A_{0\leftarrow z} \bullet f_L(t) \mid A_{0\leftarrow z} \bullet f_L(t)\rangle}{\langle f_L(t)) \mid f_L(t))\rangle}$$

$$\delta \mathrm{R} = 0 \longrightarrow \boxed{L_{z\leftarrow 0}\, A_{0\leftarrow z} \bullet f_L(t) = \lambda f_L(t)}$$

$$R_{\mathrm{opt}} = \lambda$$

Y. Lai and R.K. Lee, PRL 103, p.013902, 2009.

How squeezing is produced?



$\hat{u}(z, t)$ is related to $\hat{u}(0, t)$ and $\hat{u}^{\dagger}(0, t)$ by a linear transform

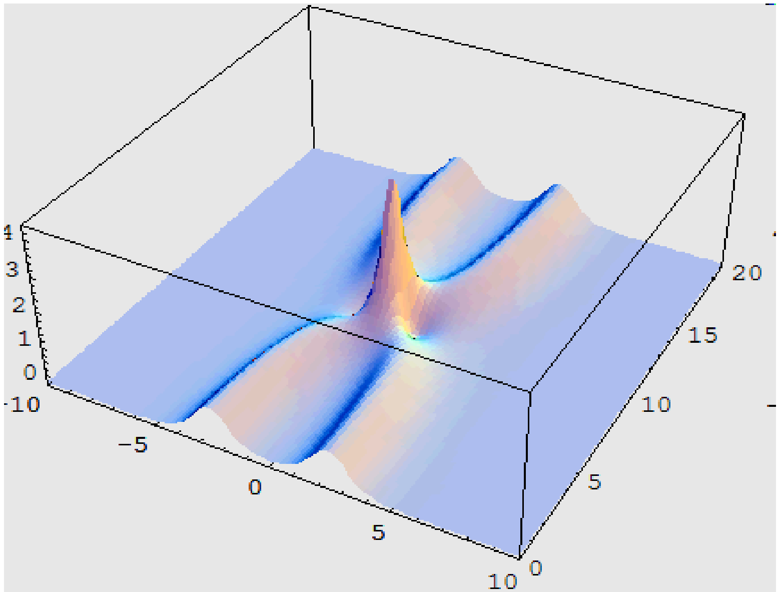
The original quantum state are multi – mode independent coherent states.

The new quantum state are multi – mode entangled gaussian states.

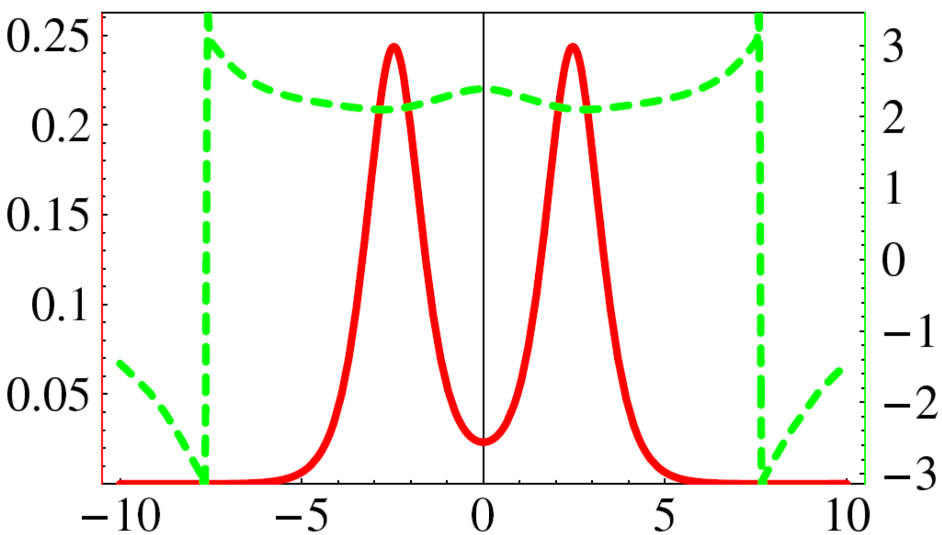
$$\hat{M} = \langle f_L(t) \mid u(z, t)\rangle = \langle F_L(t) \mid u(0, t)\rangle$$

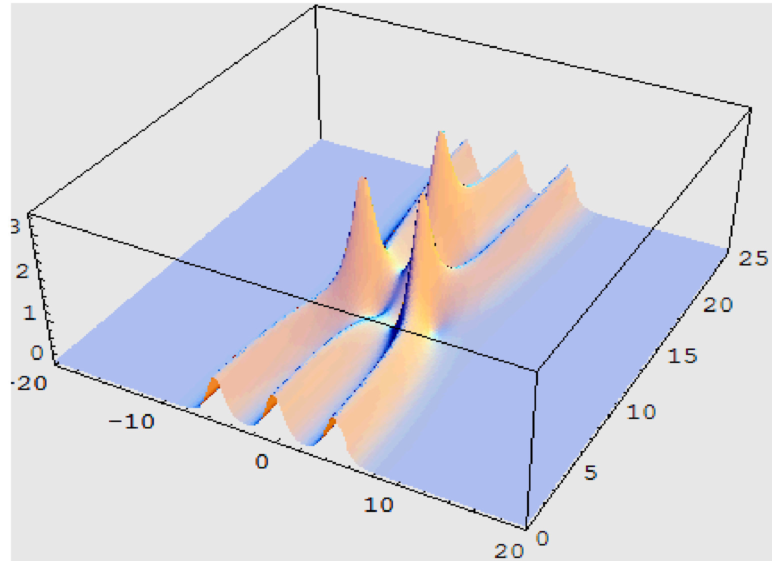
$$\mathrm{Var}[\hat{M}(z)] = \frac{1}{4} \int \mid F_L(t) \mid^2 d\, t$$

Multi-partite solitons

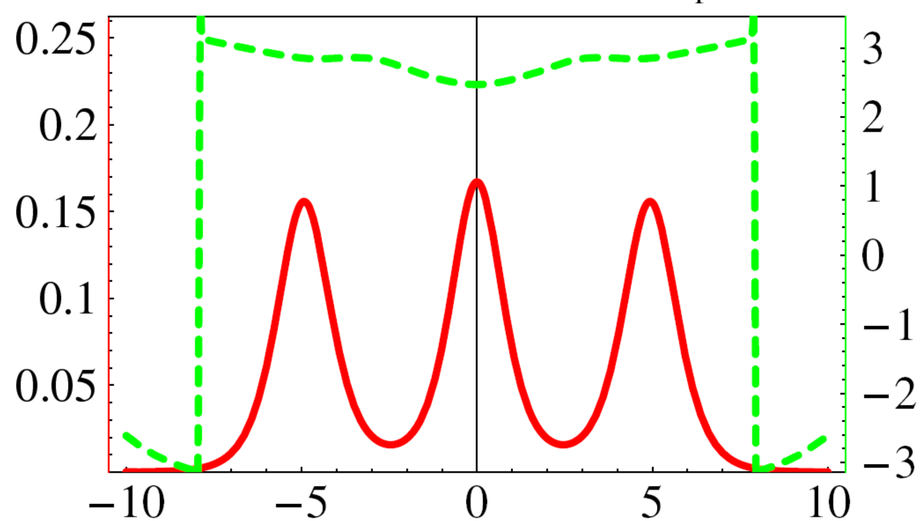


Intensity and phase of f_{opt}





Intensity and phase of f_{opt}



How squeezing leads to entanglement

$f_1(t) \propto f_{opt}(t)$ for $t > 0$

$f_2(t) \propto f_{opt}(t)$ for $t < 0$

$\hat{q}_1 = < f_1 | \hat{u} >, \ \hat{p}_1 = < i f_1 | \hat{u} >, \ \hat{q}_2 = < f_2 | \hat{u} >, \ \hat{p}_2 = < i f_2 | \hat{u} >.$

$f_1(t) + f_2(t)$ **: the optimum squeezing/anti-squeezing mode.**

$f_1(t) - f_2(t)$ **: orthogonal to the optimum mode.**

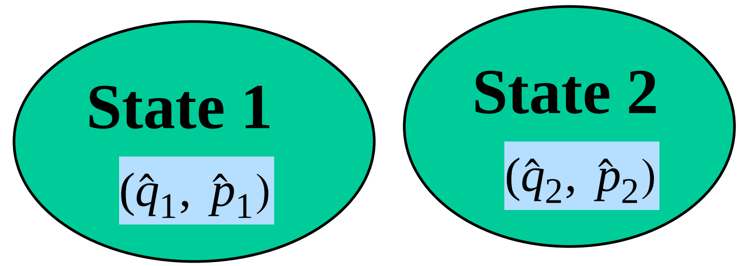
$$\text{Squeezing ratio of } \mathrm{Var}[\hat{q}_1 + \hat{q}_2]\,\mathrm{Var}[\hat{p}_1 - \hat{p}_2] \leq \frac{\lambda_{opt}}{\lambda_{snd}} < 1$$

$$\mathrm{Var}[\hat{q}_1 + \hat{q}_2] = \lambda_{opt}, \qquad \mathrm{Var}[\hat{p}_1 - \hat{p}_2] \leq \frac{1}{\lambda_{snd}}$$

Inseparability criterion of two-partite quantum states

Definition of separable quantum states:

$$\rho = \sum_i P_i \, \rho_{i,1} \otimes \rho_{i,2}$$



Sufficient criterion for inseparability:

If $\hat{q}_1$ is corrlated with $\hat{q}_2$ and $\hat{p}_1$ is corrlated with $\hat{p}_2$, and

$\mathrm{Var}[\hat{q}_1|\hat{q}_2]$*$\mathrm{Var}[\hat{p}_1|\hat{p}_2]$ < Heisenberg uncertainty product

Quantum correlation $\neq$ Quantum entanglement (inseparability)

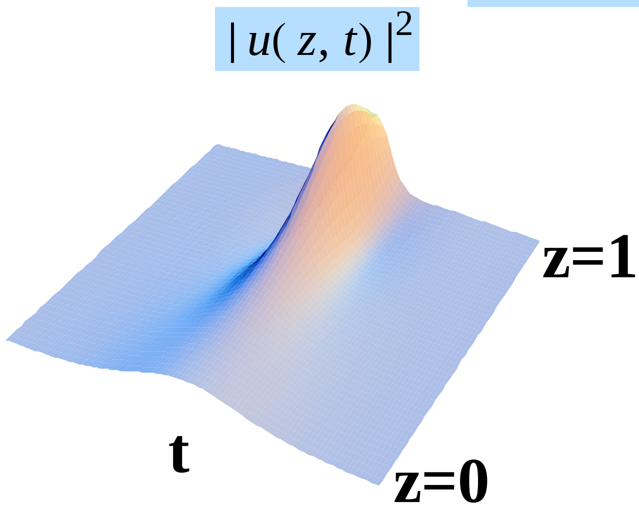
For example,

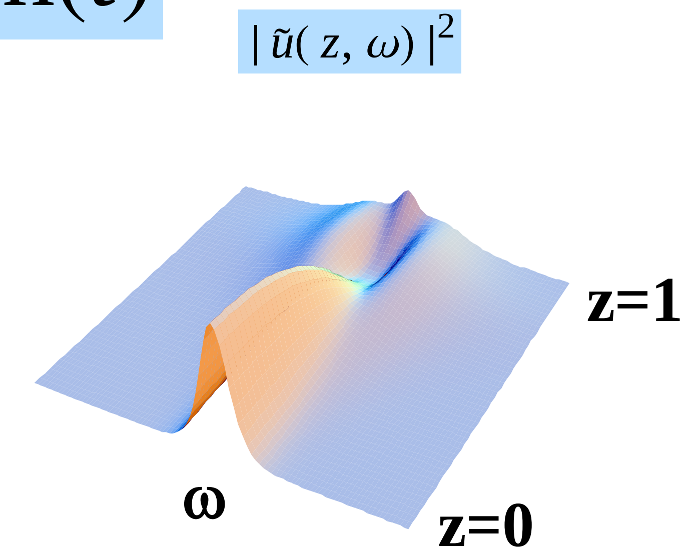
$$\rho = \int P(\alpha) \, |\alpha\rangle_1 \, |\alpha\rangle_2 \, \langle\alpha|_1 \, \langle\alpha|_2 \; d\alpha$$

Correlated but not entangled.

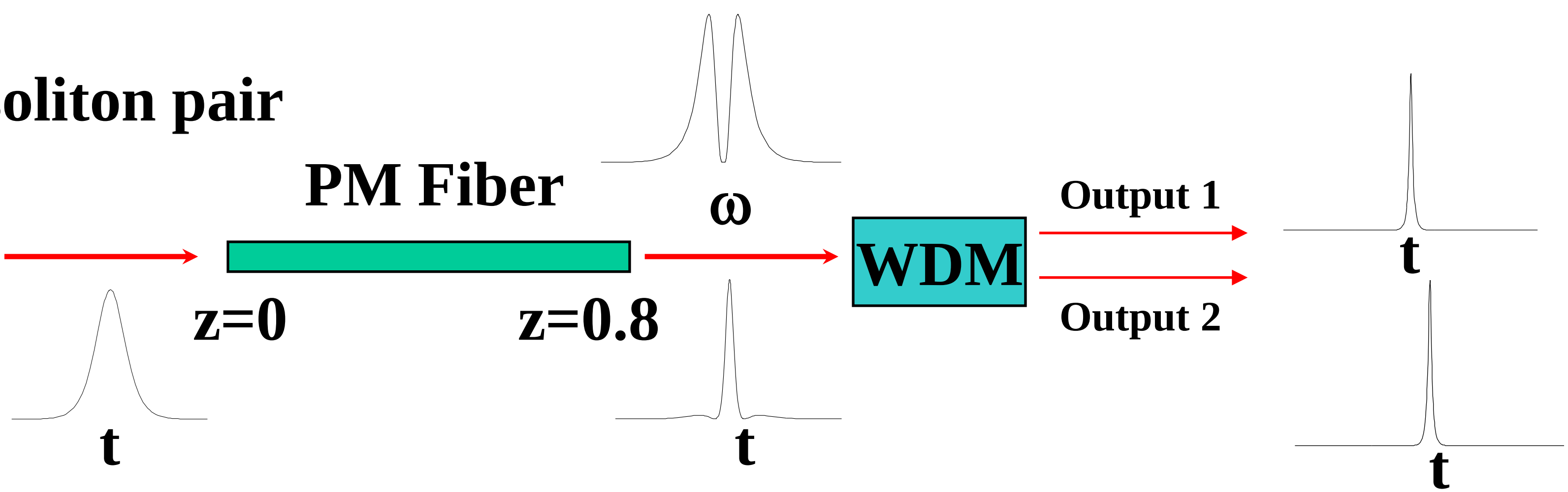
Entangled frequency multiplexed quantum solitons (I)

$$u(z, t) = 2\,\mathrm{sech}(t)$$





WDM soliton pair



Entangled frequency multiplexed quantum solitons (II)

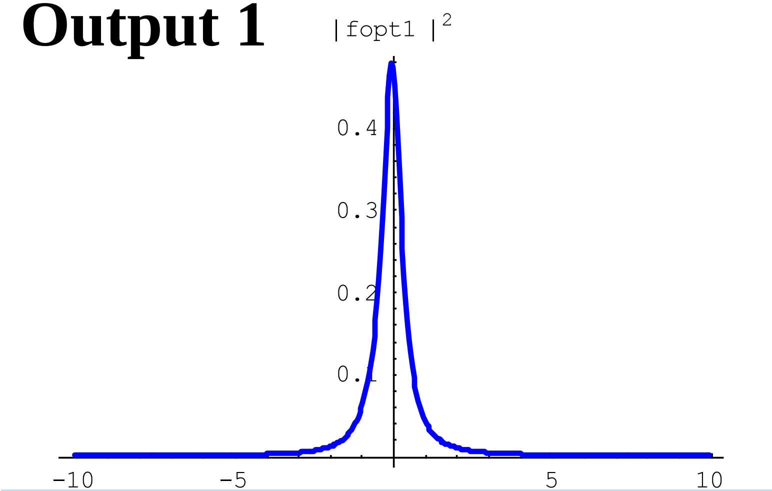
$\lambda_{opt} = -24$ dB

$\lambda_{snd} = -17$ dB

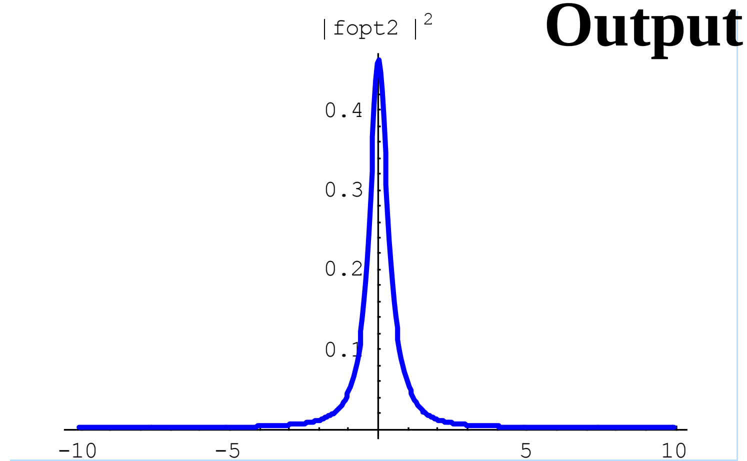
Squeezing ratio of $\mathrm{Var}[\hat{q}_1 + \hat{q}_2]\,\mathrm{Var}[\hat{p}_1 - \hat{p}_2] < -7$ dB

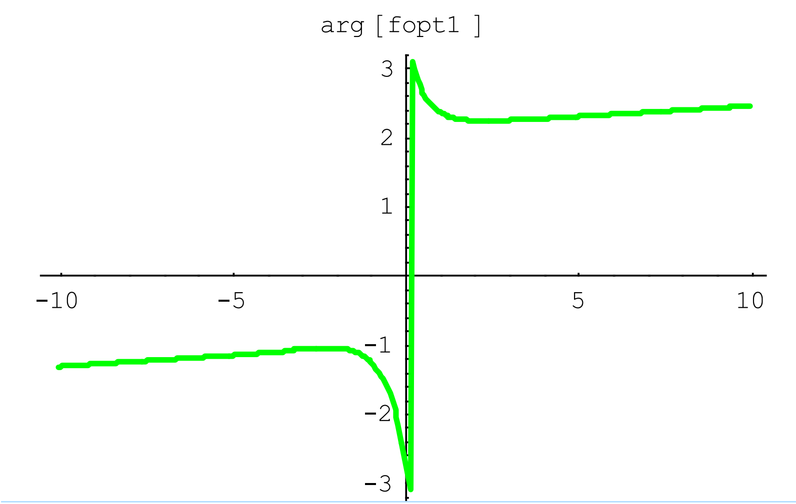
Projection mode functions

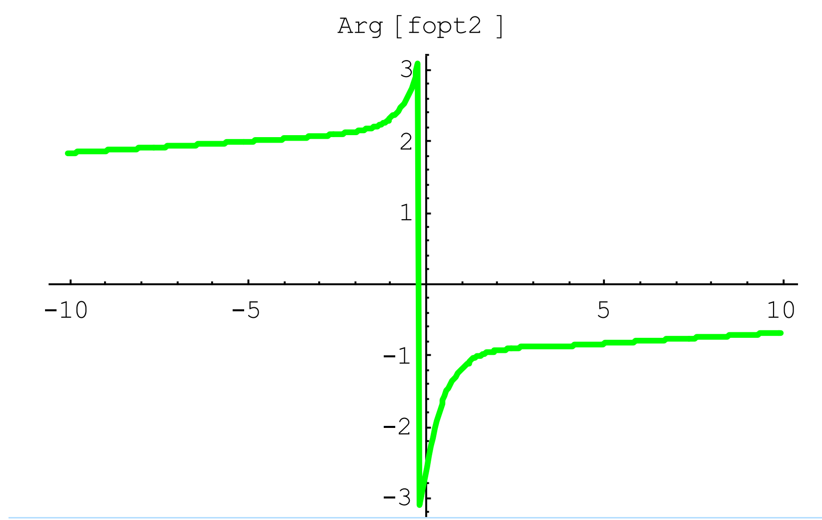
Output 1



Output 2





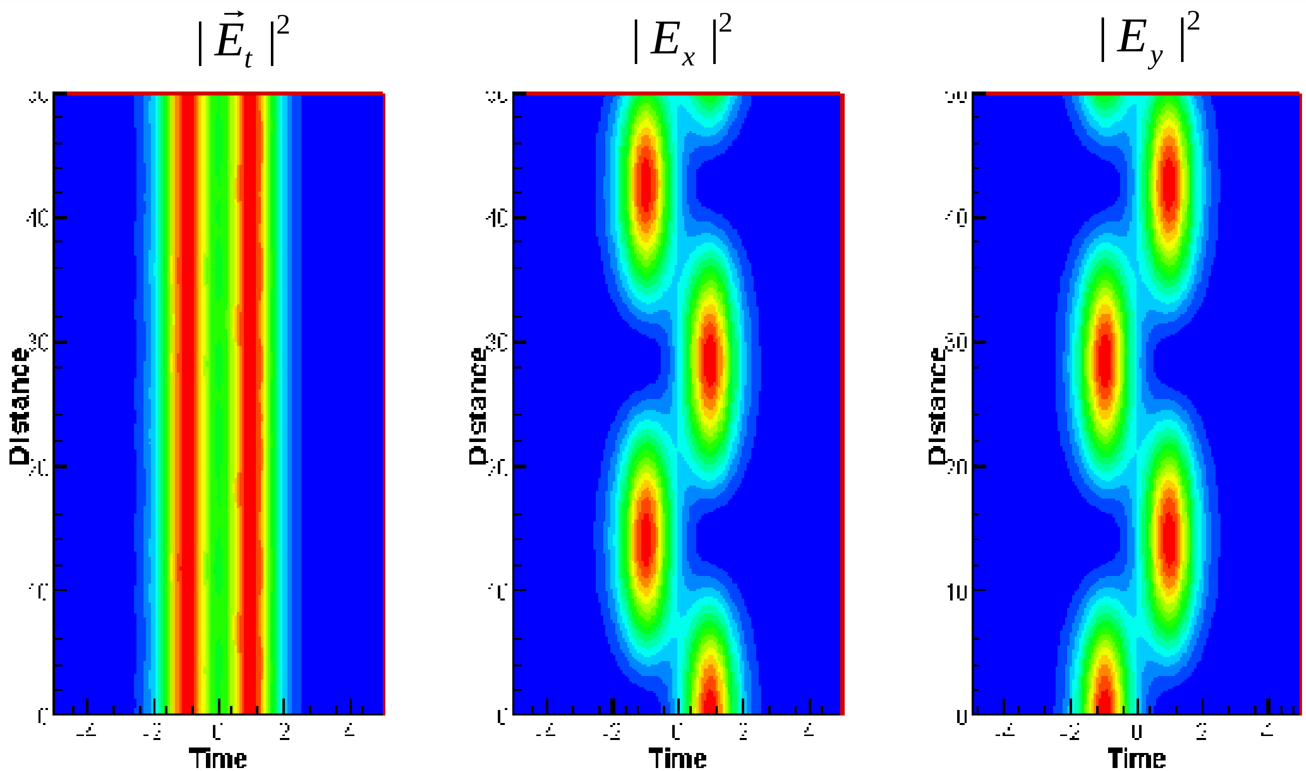


PDM bound solitons

$$i\frac{\partial U}{\partial z} + \frac{1}{2}\frac{\partial^2 U}{\partial t^2} + A|U|^2 U + B|V|^2 U = 0$$
$$i\frac{\partial V}{\partial z} + \frac{1}{2}\frac{\partial^2 V}{\partial t^2} + A|V|^2 V + B|U|^2 V = 0$$

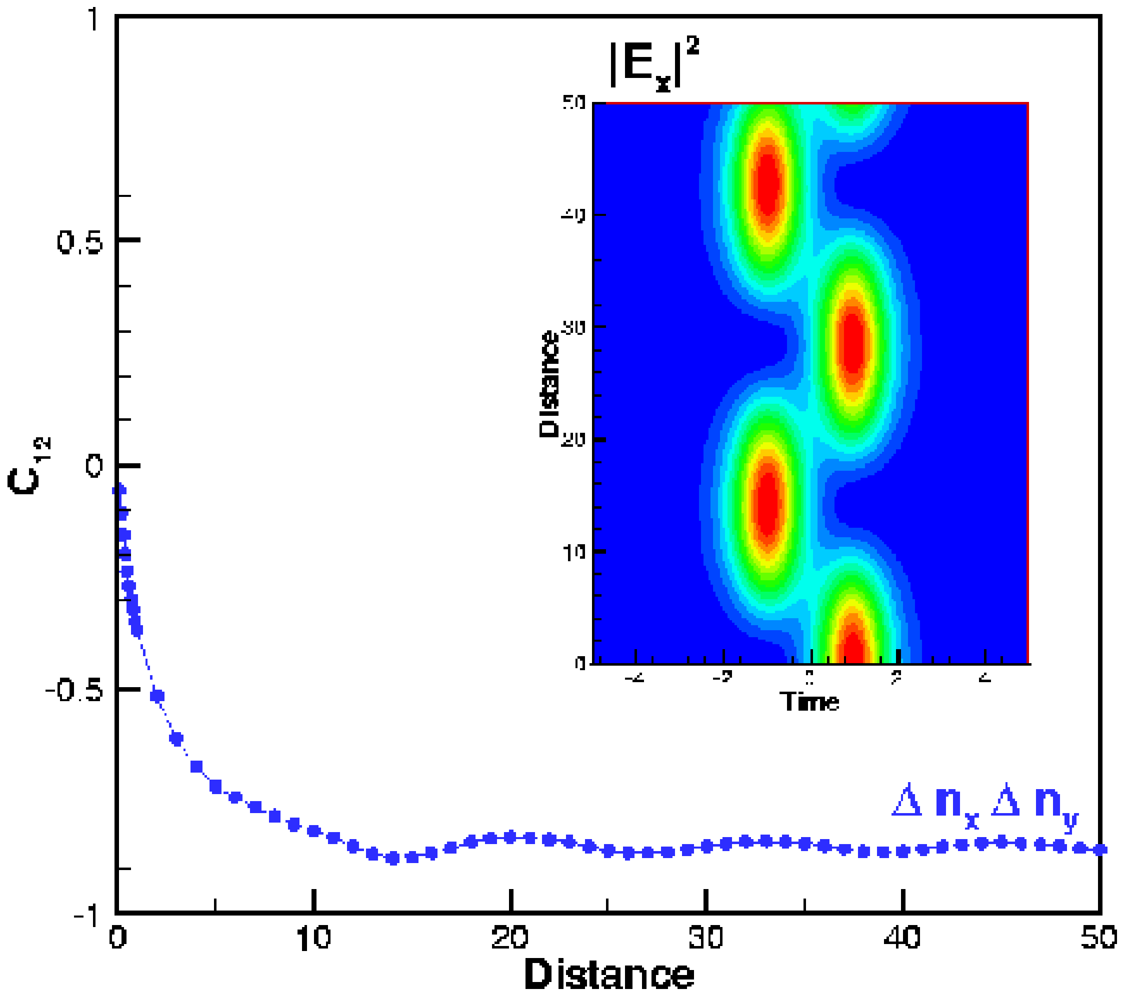
and $A = 1/3$, $B = 2/3$

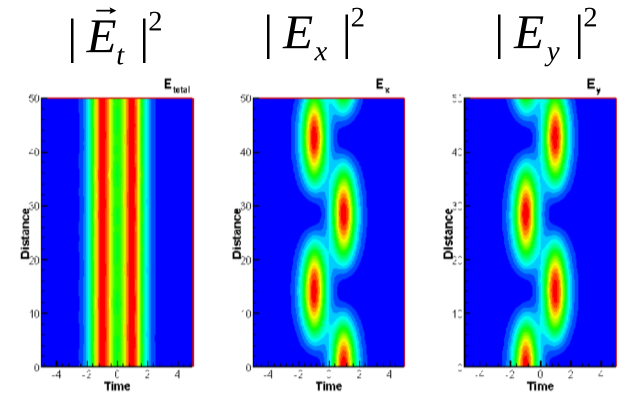
U,*V*: Fields in circular polarizations



M. Haelterman et al., Optics Letters 18, 1406 (1993).

Quantum correlation of PDM soliton pairs

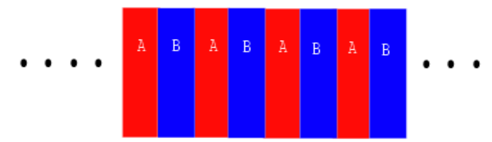




R.-K. Lee, Y. Lai, and B. A. Malomed, Phys. Rev. A 71, 013816 (2005)

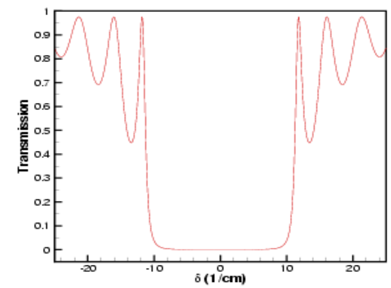
Fiber Bragg Grating Solitons

Solitons in 1D nonlinear photonic crystals

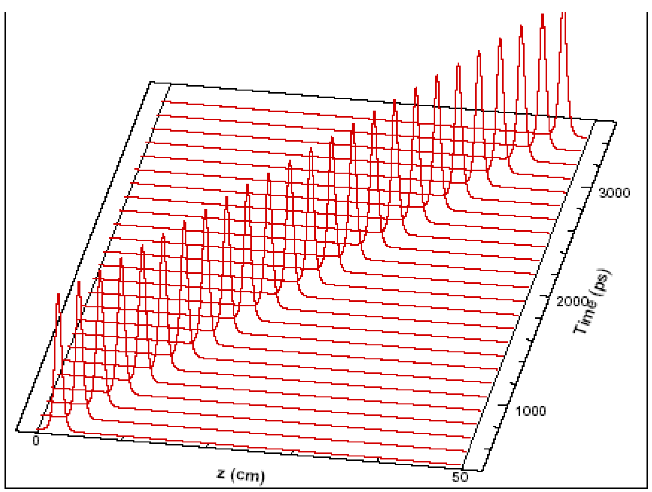


$$\frac{1}{v_g}\frac{\partial}{\partial t}U_a(z,t) + \frac{\partial}{\partial z}U_a = i\delta U_a + i\kappa U_b + i\Gamma|U_a|^2U_a + 2i\Gamma|U_b|^2U_a$$

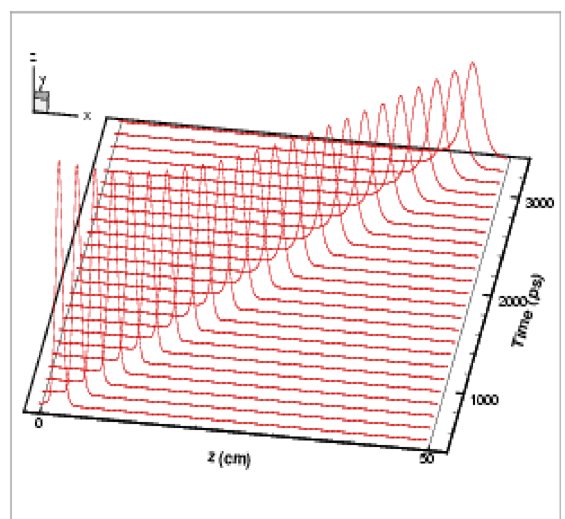
$$\frac{1}{v_g}\frac{\partial}{\partial t}U_b(z,t) - \frac{\partial}{\partial z}U_b = i\delta U_b + i\kappa U_a + i\Gamma|U_b|^2U_b + 2i\Gamma|U_a|^2U_b$$



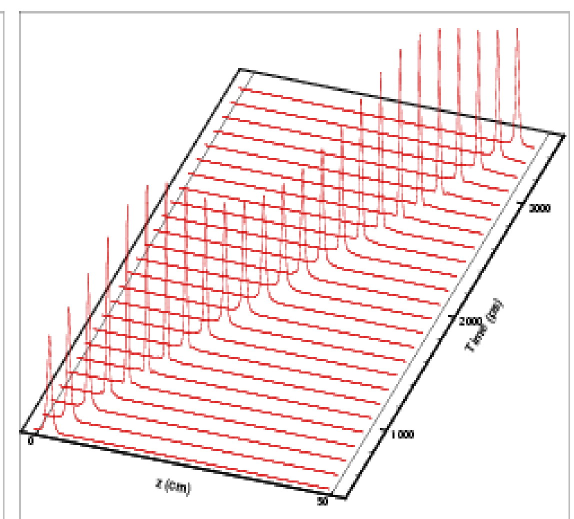
stationary



below

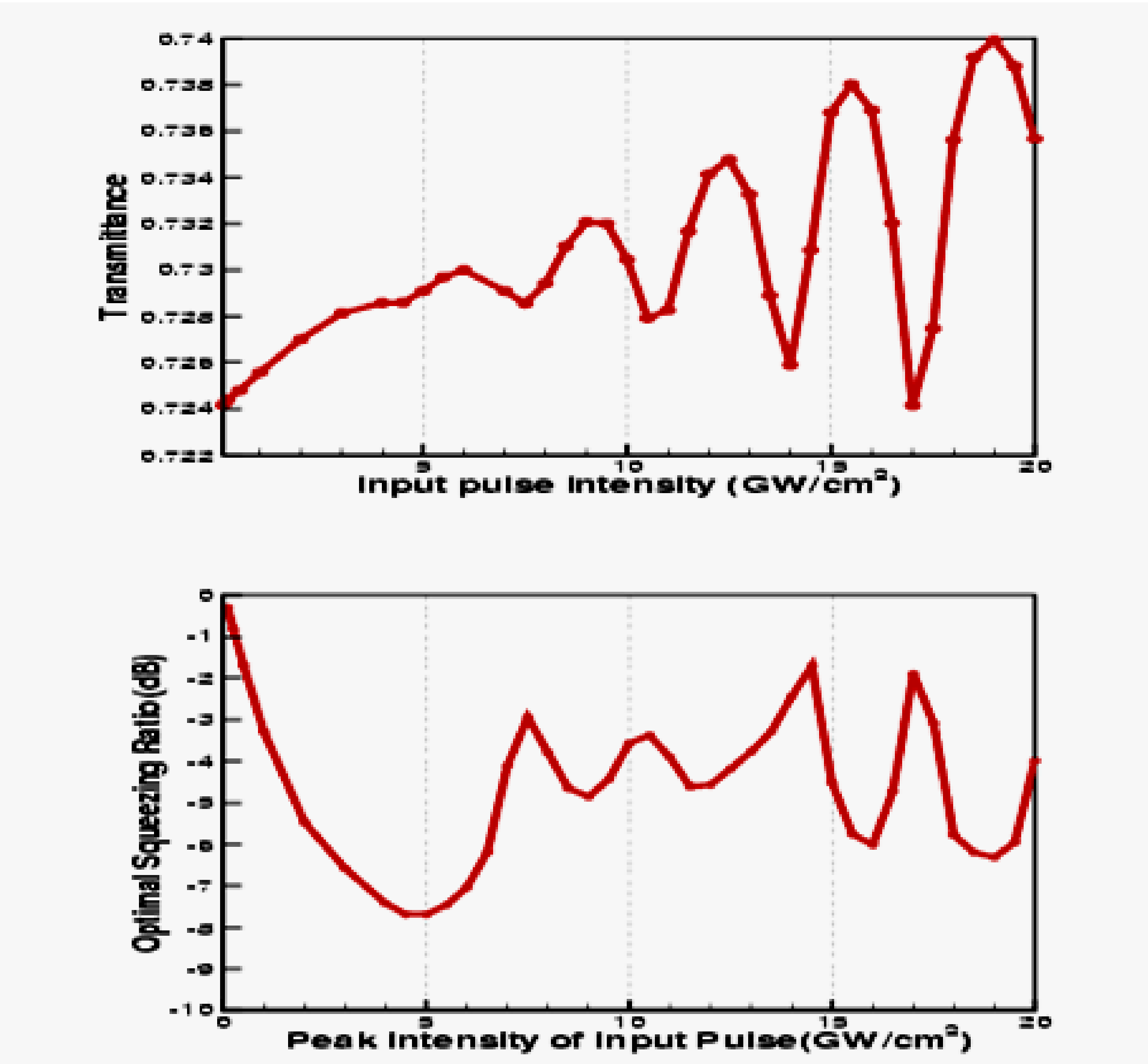


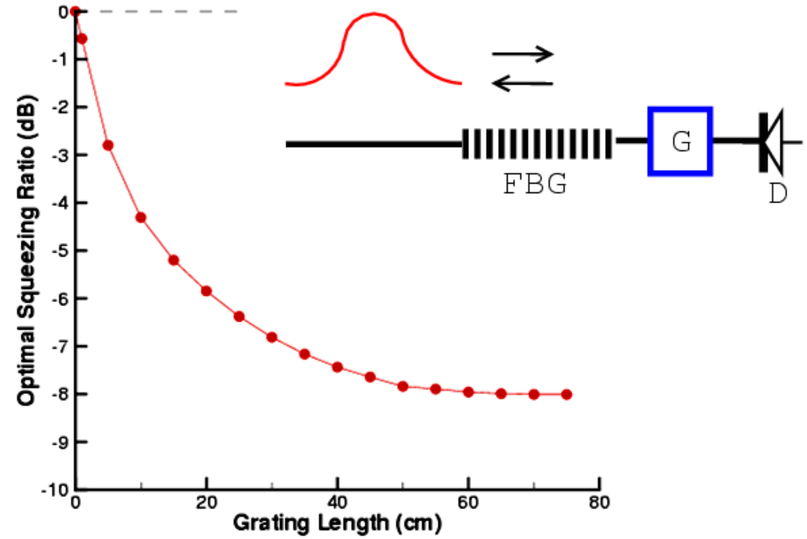
above



B.J. Eggleton *et al.*, Phys. Rev. Lett. **76,** 1627 (1996)

Amplitude squeezing of fiber Bragg grating solitons





$$\hat{M} = M + \Delta\hat{M}$$

$$R = \frac{\left\langle \Delta\hat{M}^{2} \right\rangle}{\left\langle \Delta\hat{M}^{2} \right\rangle_{coherent\ state}}$$

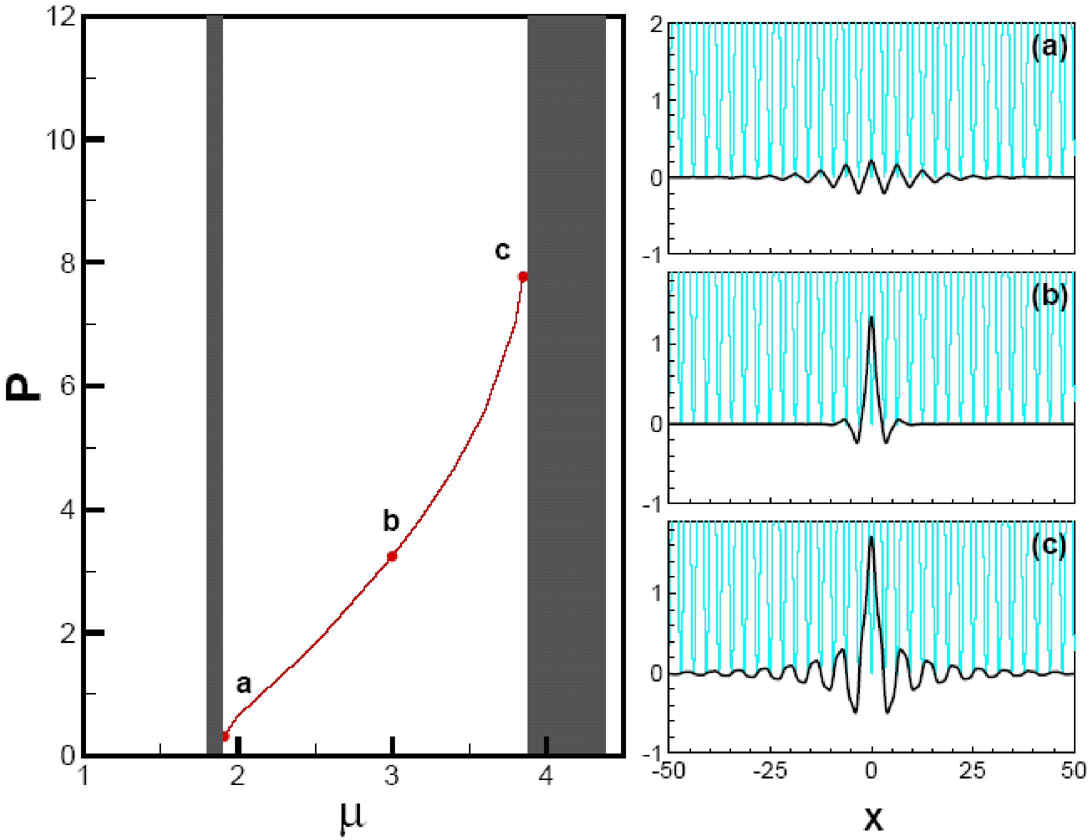
R<1 : Squeezing

R>1 : Anti-squeezing

R.K. Lee and Y. Lai, Phys. Rev. A 69, 021801(R) (2004)

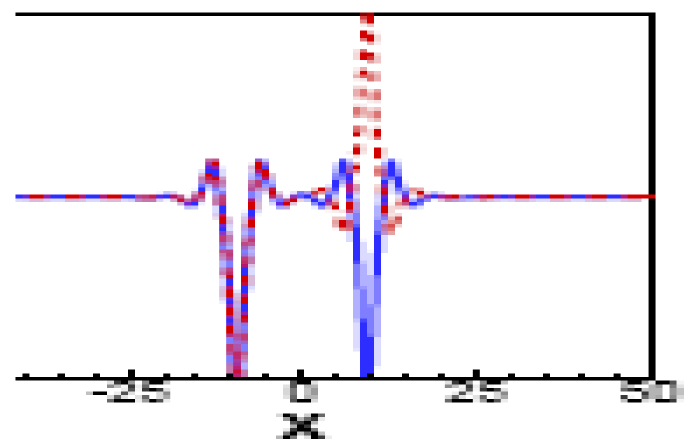
BEC matter-wave gap solitons

$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{1}{2}\frac{\partial^2 \Psi}{\partial x^2} + V(x)\Psi + g_{1D}|\Psi|^2\Psi,$$

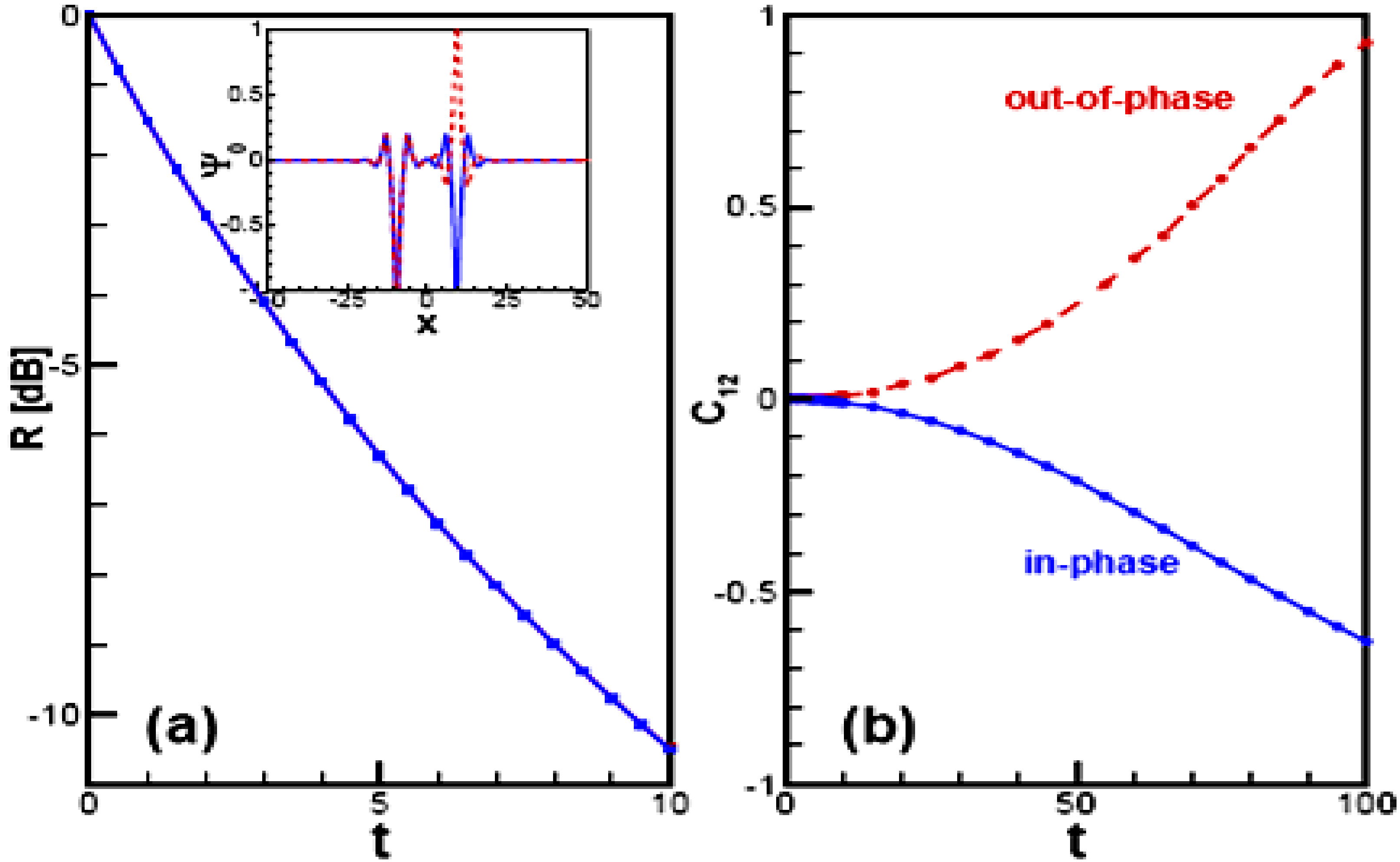


$$V(x) = V_0 \sin^2(x)$$

$$\Psi(t,x) = \psi(x)\exp(-i\mu t)$$



Quantum noises of matter-wave gap solitons

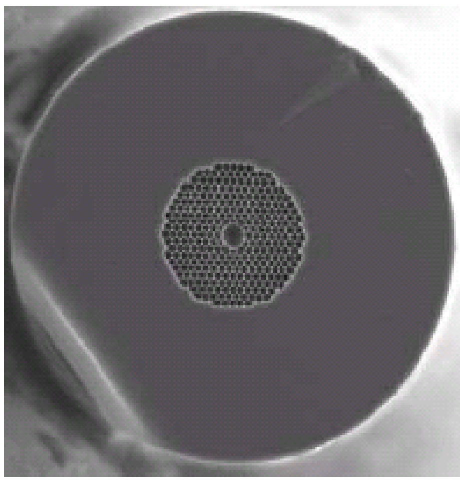


R.-K. Lee, E. A. Ostrovskaya, Y. S. Kivshar, and Y. Lai, Phys. Rev. A 72, 033607 (2005).

Quantum properties of SIT solitons

Squeezing through self induced transparency in a microstructured hollow core fibre

Ch. Marquardt, U.L. Andersen and G. Leuchs



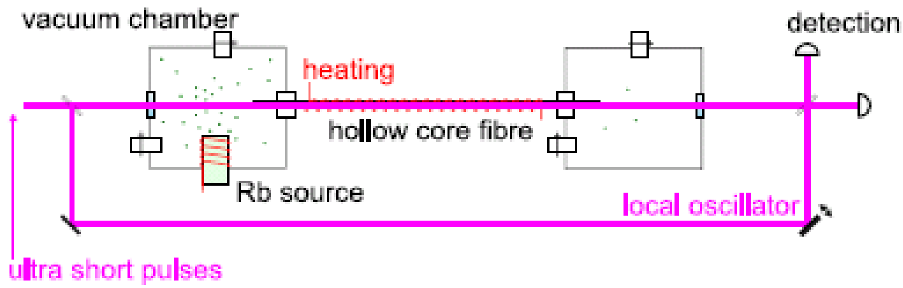


Figure 2: *Experimental setup of Rb filling chambers and homodyne detection of light pulses propagating through a Rb vapour filled hollow core fibre.*

Quantum equations of SIT solitons

$$\int_{z}^{z+\Delta z} \hat{P}(z,t)\,dz = \sum_{z \le z_j \le z+\Delta z} \hat{p}_j(t)$$

$$\int_{z}^{z+\Delta z} \hat{N}(z,t)\,dz = \sum_{z \le z_j \le z+\Delta z} \hat{n}_j(t)$$

$$\frac{\partial \hat{U}(z,t)}{\partial t} = -c\,\frac{\partial \hat{U}(z,t)}{\partial z} + K\,\hat{P}(z,t)$$

$$\frac{\partial \hat{P}(z,t)}{\partial t} = K\,\hat{N}(z,t)\,\hat{U}(z,t)$$

$$\frac{\partial \hat{N}(z,t)}{\partial t} = -2\,K\left\{\hat{P}^{\dagger}(z,t)\,\hat{U}(z,t) + \hat{U}^{\dagger}(z,t)\,\hat{P}(z,t)\right\}$$

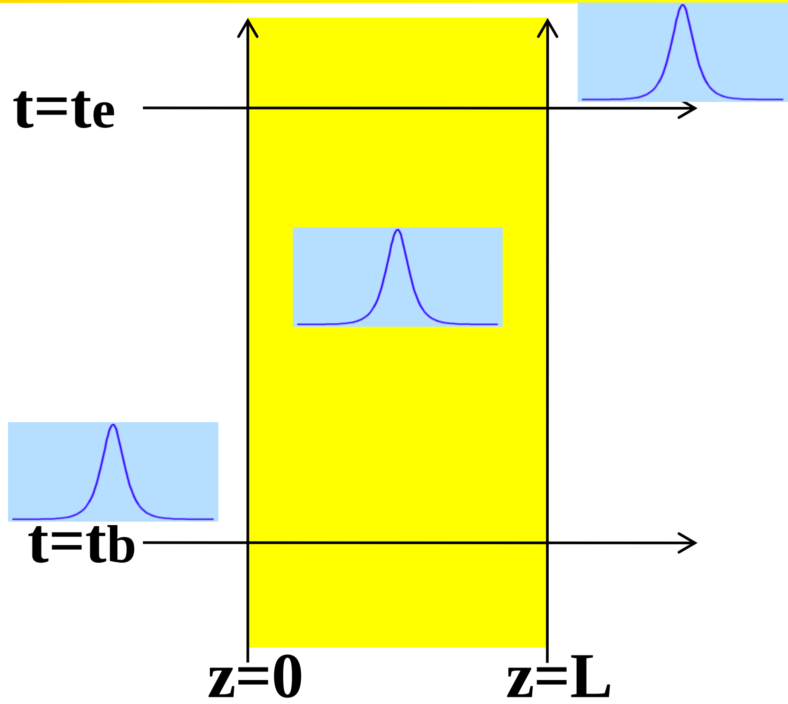
For the Bethe's ansatz approach, see S. John and V. I. Rupasov, *Europhys. Lett.* 46, p.326, 1999.

Linearized equations of SIT solitons

$$\frac{\partial}{\partial t}\hat{u} = -\frac{\partial}{\partial z}\hat{u} + \frac{r}{2}\hat{p},$$

$$\frac{\partial}{\partial t}\hat{p} = \frac{1}{2}(U_0\,\hat{n} + N_0\,\hat{u})$$

$$\frac{\partial}{\partial t}\hat{n} = -\left(P_0^*\,\hat{u} + U_0\,\hat{p}^\dagger + U_0^*\,\hat{p} + P_0\,\hat{u}^\dagger\right),$$



$$\hat{M}(t_e) = \int \left[f_L{}^*(z)\,\hat{u}(z,t_e) + f_L(z)\,\hat{u}^\dagger(z,t_e)\right] dz$$

$$\hat{M}(t_e) = \int dz \left[u^{A*}(z,t_b)\,\hat{u}(z,t_b) + u^{A}(z,t_b)\,\hat{u}^\dagger(z,t_b) + p^{A*}(z,t_b)\,\hat{p}(z,t_b) + p^{A}(z,t_b)\,\hat{p}^\dagger(z,t_b) + n^{A}(z,t_b)\,\hat{n}(z,t_b)\right]$$

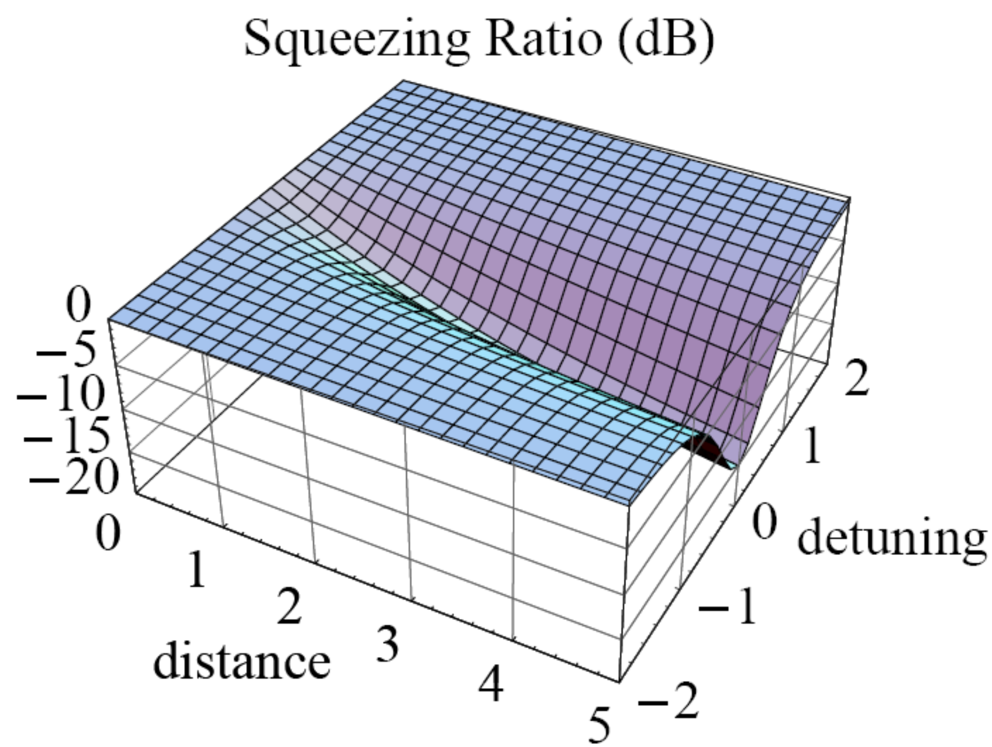
Squeezing of SIT solitons

$$\Delta n(t) = \Delta n_0 \ ,$$

$$\Delta\theta(t) = \Delta\theta_0 + \frac{\partial\omega}{\partial n_0}\Delta n_0 t + \frac{\partial\omega}{\partial p_0}\Delta p_0 t$$

$$\Delta p(t) = \Delta p_0 \ ,$$

$$\Delta x(t) = \Delta x_0 + \frac{\partial v_g}{\partial n_0}\Delta n_0 t + \frac{\partial v_g}{\partial p_0}\Delta p_0 t$$



At resonance, the squeezing is actually through the coupling of the photon number and the pulse position operators.

Y. Lai and H.A. Haus, Phys. Rev. A 42, 2925(1990).

PHYSICAL REVIEW A 80, 033839 (2009)

Quantum squeezing and correlation of self-induced transparency solitons

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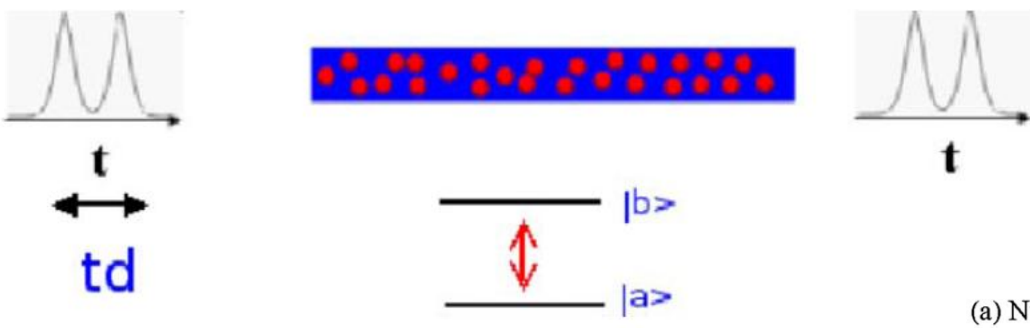
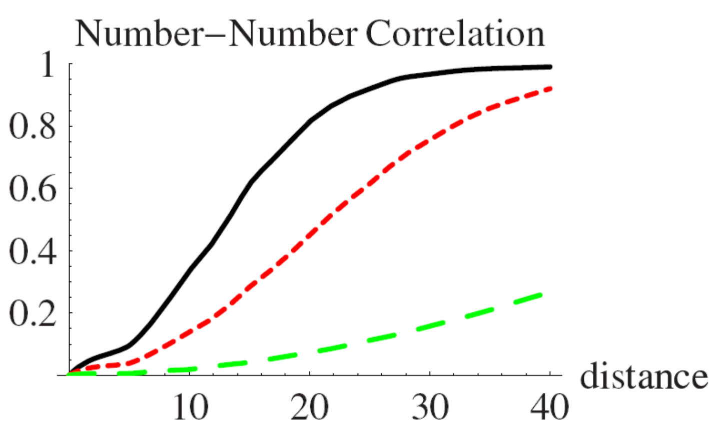
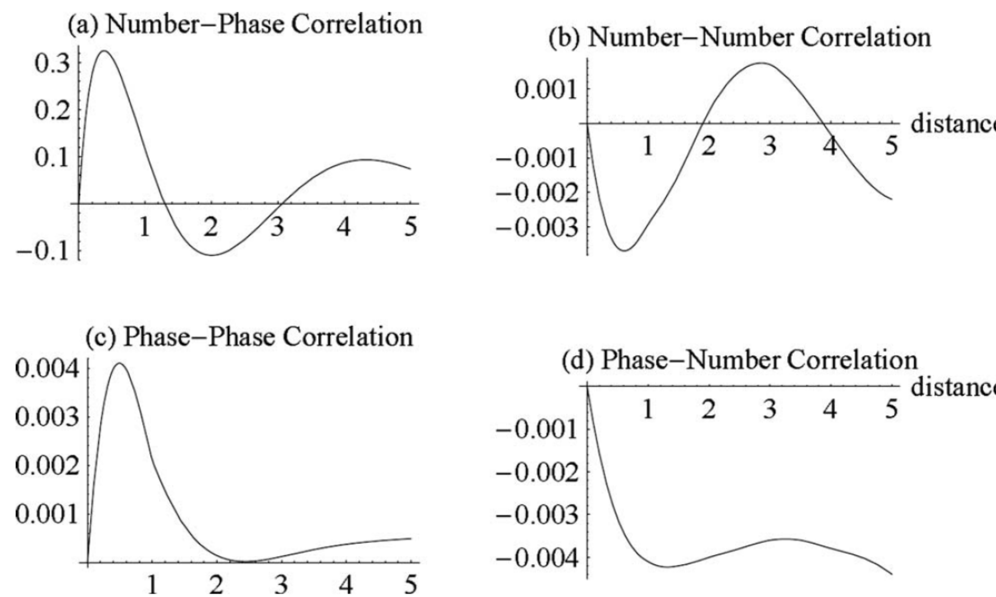


In-phase soliton pairs



Out-of-phase soliton pairs



Conclusions

- Theories of quantum nonlinear optical propagation are reviewed.
- Quantum soliton, squeezing, correlation, and entanglement are explained.
- How squeezing leads to entanglement is clarified.
- Entangled quantum solitons can be generated through nonlinear interaction.
- Time-, polarization-, or frequency-multiplexed schemes are analyzed.
- Different optical soliton platforms are investigated.