Photon-Number Squeezing by Temporal Modulation of Solitons

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Abstract We show that temporal modulation of solitons after propagation in a fiber gives rise to photon-number squeezing. Modulation that removes central part of the pulse can give noise reduction more than 3dB.

1. Introduction

Much interest has recently been paid to efficient generation of squeezed radiation, which can be a source of continuous-variable entangled beams[1]. Exploiting fiber nonlinearity is a promising way to generate such squeezed radiation. Photon-number squeezing larger than 10dB and 5dB can be expected by the use of highly asymmetric Sagnac fiber interferometers and by spectrally filtered optical solitons, respectively[2,3]. In the latter approach, noise reduction below the shot noise level is achieved by rejecting spectral components whose photon-number fluctuation positively correlates to those of the other spectral components. The same scheme but for classical noise reduction can be applied to signal stabili-zation or regeneration in long-distance fiber-optic communication systems[4,5]. The quantum noise reduction is also expected by signal manipulation in the time domain making use of nonlinearity-induced photon-number correlation between different temporal components. In this paper, the extent of quantum noise reduction is numerically analyzed for temporally modulated optical fiber solitons.

2. Analysis

The analysis is based on the linearization approximation for solving the quantum nonlinear Schrödinger equation (NLSE)

$$i\frac{\partial \hat{U}}{\partial z} - \frac{1}{2}\beta\frac{\partial^2 \hat{U}}{\partial t^2} + \gamma\frac{\hbar\omega}{\Delta T}\hat{U}^+\hat{U}\hat{U} = 0\,, \qquad (1)$$

where β and γ are the group-velocity dispersion and nonlinear coefficients of the fiber and $\hat{U}^+\hat{U}$ is an operator representing the photon number contained in a time slot whose duration is ΔT . (1) is linearized by setting $\hat{U} = U + \hat{u}$, where U is the classical envelope of the pulse and $\hat{u}$ is the operator for the quantum fluctuation. Solving the linearized equation for $\hat{u}$ gives an expression relating $\hat{u}_i$ of the i-th time slot at the fiber exit to those at the fiber entrance $\hat{a}_j$ (j=1~J, J: number of time slots used in the simulation) that account for vacuum fluctuation of the input field. The resulting expression in the matrix form for the field operator at the fiber exit is[6]

$$\hat{\mathbf{U}}_1 = \mathbf{U} + \mathbf{A}\hat{\mathbf{a}} + \mathbf{B}\hat{\mathbf{a}}^+ \qquad (2)$$

where $\mathbf{U}$ is the averaged envelope of the pulse obtained by solving the classical NLSE and the coefficient matrices $\mathbf{A}$ and $\mathbf{B}$ are composed of μ_{jk} and ν_{jk} ($A_{jk} = \mu_{jk}$ and $B_{jk} = \nu_{jk}$) given in eq.(2.13) in ref.6. After the transmission through the fiber, spectral filtering and temporal modulation in general are assumed to be applied to the pulse. The output field is then given by

$$\hat{\mathbf{U}}_2 = \mathbf{M}_T\mathbf{F}_T\mathbf{U} + \mathbf{M}_T\mathbf{F}_T\mathbf{A}\hat{\mathbf{a}} + \mathbf{M}_T\mathbf{F}_T\mathbf{B}\hat{\mathbf{a}}^+ + \mathbf{M}_T\mathbf{F}_R\hat{\mathbf{b}} + \mathbf{M}_R\hat{\mathbf{c}}$$

where $\mathbf{F}_T$ and $\mathbf{M}_T$ are matrices representing the operations of the filter and the modulator, respectively, and $\hat{\mathbf{b}}$ and $\hat{\mathbf{c}}$ are vacuum fluctuations introduced by the loss of the filter and the modulator. $\mathbf{F}_T$, $\mathbf{F}_R$, $\mathbf{M}_T$, and $\mathbf{M}_R$ are given by

$$\mathbf{F}_T = \mathbf{Q}^{-1}\,\mathbf{diag}\left[\left|H(\omega_i)\right|\right]\mathbf{Q}\,,$$

$$\mathbf{F}_R = \mathbf{Q}^{-1}\,\mathbf{diag}\left[\sqrt{1-\left|H(\omega_i)\right|^2}\right]\mathbf{Q}\,,$$

$$\mathbf{M}_T = \mathbf{diag}\left[\left|m(t_i)\right|\right], \quad \text{and}$$

$$\mathbf{M}_R = \mathbf{diag}\left[\sqrt{1-\left|m(t_i)\right|^2}\right],$$

where $\mathbf{Q}$ is the matrix representing the discrete Fourier transform and $\mathbf{diag}[f_i]$ means a diagonal matrix whose i-th component is given by f_i. $H(\omega)$ and $m(t)$ are the filter transfer function and the modulator function in the time domain, respectively. The noise reduction is quantified by the Fano factor defined by $\left(\langle\hat{N}\hat{N}\rangle - \langle\hat{N}\rangle^2\right)/\langle\hat{N}\rangle$, where $\hat{N} = \sum_i \hat{U}_{2i}^+\hat{U}_{2i}$ is the total photon number.

3. Numeircal results

In the first numerical simulation, a 1.5ps-width soliton is transmitted over three soliton periods and either a Gaussian temporal modulation $m_1(t) = \exp(-\alpha t^2/2)$ or an inverse-Gaussian modulation $m_2(t) = \sqrt{1-\exp(-\alpha t^2)}$ is applied. The time origin $t = 0$ coincides with the pulse peak. For the latter modulation $m_2(t)$, the central part of the pulse is attenuated. Fig.1 shows the noise reduction and energy loss by the modulator versus modulation temporal width $\Delta t = \sqrt{4 \ln 2/\alpha}$ for both types of the modulation. In the anomalous-dispersion regime of the fiber, the noise in the central part of the pulse is self-enhanced through temporal pulse compression. This leads to noise enhancement when the modulator of the type $m_1(t)$ removes photons distributed in the pulse tails as shown in Fig.1(a). This corresponds to the fact that transmission of classical solitons is destabilized by the application of synchronous amplitude modulation alone for the purpose of suppressing the Gordon-Haus timing jitter[7]. When the notch-type modulation $m_2(t)$ is applied, on the other hand, noise reduction can be achieved as shown in Fig.1(b).

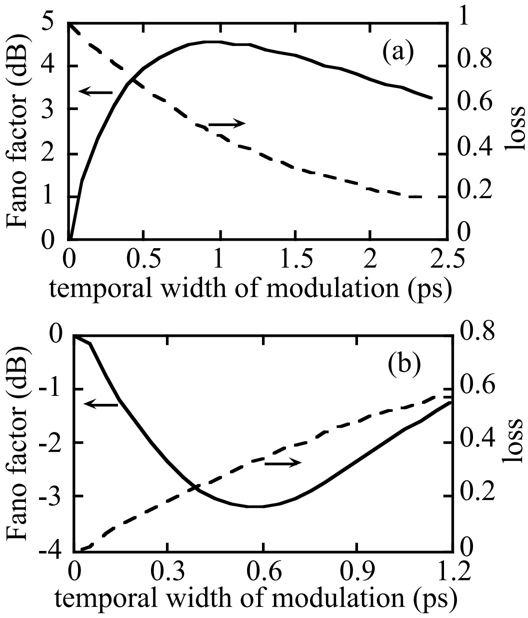

Fig.1. Noise enhancement and reduction by temporal modulation. (a) Gaussian modulation function $m_1(t)$ and (b) Inverse-Gaussian (notch) modulation function $m_2(t)$ are applied.

Fig.2 shows the noise reduction obtained by the inverse-Gaussian modulation with the notch width of 0.6ps versus transmission distance. 3.2 dB noise reduction is obtained for a fiber length of 3.0 soliton periods. In Fig.2 noise reduction obtained by a Gaussian spectral filter (band-width=250GHz) is also shown. It is interesting to note that the maximum noise reduction is obtained almost at the same fiber length both for the spectral filtering and temporal modulation. This means that the noise in the spectral tails of the pulse is correlated to the noise contained near the temporal peak of the pulse.

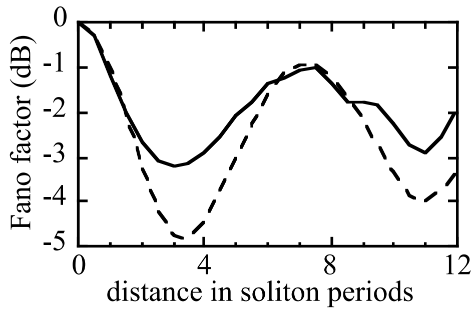

Fig.2. Noise reduction by temporal modulation (solid curve) or by spectral filtering (dashed curve).

4. Conclusion

It was numerically shown that temporal modulation of solitons after propagation in a fiber gives rise to photon-number squeezing. Modulation that removes central part (in the time domain) of the pulse can yield noise reduction more than 3dB. Optimization of the modulator function and combination with other schemes such as spectral filtering will further enhance the ability of noise reduction.

Although realization of such synchronous temporal modulation, which is very fast and should have no extra loss, is difficult in practice, the use of the time-lens devices[8] may alleviate the difficulty.

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