Numerical Simulations on Quantum Noise Squeezing for Soliton-like Pulses in Optical Fiber

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Abstract — **Generation of light with nonclassical properties, such as squeezed light, has gathered a lot of attention because of possible uses in such areas as quantum state engineering, quantum imaging, continuous variable quantum computing, and detection of gravitational waves. Squeezed light is generally produced by transporting light through a nonlinear medium. One such media is Kerr-nonlinear optical fibres. We aim to find the parameters for a fibre polarization squeezing setup by studying the dependencies of quantum noise suppression on the duration of the pulse and the input power. This is performed by modeling the light field propagation using the split-step Fourier method to numerically solve the stochastic nonlinear Schrödinger equation obtained by using the Wigner representation. This equation includes such physical effects as damping, quantum loss noise, dispersion, Kerr and Raman nonlinearities, and stochastic Raman noise.**

I. INTRODUCTION

Squeezed light is a quantum state of the light field for which the fluctuation of a certain quadrature is lower than the limit achieved in the coherent states (to satisfy Heisenberg's uncertainty principle, the variance of the conjugated quadrature is above the limit) [1]. The generation of squeezed states of light allows for quantum noise suppression, which is currently in high demand due to such applications as quantum state engineering, quantum imaging, continuous variable quantum computing, and detection of gravitational waves, along with any other ultrahigh precision measurements [1]. Squeezed light states are generated by propagating the pulses through the nonlinear medium. Nonlinear systems that can be used for that purpose include parametric down-conversion and amplification systems, semiconductor lasers, atomic ensembles, and optical fibres. Using the Kerr effect in optical fibers to achieve squeezing has several advantages, such as the ability to couple the squeezed light directly into the fibre-based optical systems. The best squeezing achieved in the fiber squeezing experiment is -6.8 dB (if you take losses in the experimental setup into account, the squeezing generated in this system is-10.4 dB) [2].

Strength of the possible quantum noise suppression in fibre systems varies greatly depending upon the parameters of the pulse. Therefore, an analysis of those dependencies is required for experimental squeezing implementation. To find how the duration and energy of soliton-like pulse affect quantum noise suppression, we perform numerical simulations based on the Wigner representation of the quantum system to determine how those parameters influence the theoretical squeezing achievable.

II. NUMERICAL MODEL

The simulation of nonclassical pulse evolution that includes quantum noise effects is done by using Wigner representation to obtain stochastic nonlinear Schrödinger equation with Raman effects added[3,4]:

$$\frac{\partial A(t,z)}{\partial z} = +\left[i\gamma \int R(t-\tau)|A(\tau,z)|^2 d\tau + \Gamma^R(t,z)\right] A(t,z) - \alpha A(t,z) + \Gamma(t,z) + i\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2}A(t,z). \qquad (1)$$

In this equation, A is the complex amplitude, t is time in the frame of reference moving with the pulse at the group velocity, z is the coordinate along the fiber, γ is the nonlinear Kerr coefficient, α describes optical damping, β_2 is the group velocity dispersion, $R(t)$ is a function that describes Kerr and deterministic Raman nonlinear response, Γ and Γ^R are stochastic terms which represent loss-related and Raman quantum noise, respectively, distribution of which is given by [3,4]. This equation was already successfully used to create a numerical code that used the split-step Fourier method to simulate Kerr squeezing in various fibres [3,5,6]. The Raman response function used is from [2]. GAWBS is neglected in model because fibre considered has a relatively short waveguide length of 5.2 meters.

We model the propagation of pairs of pulses with orthogonal polarization through the waveguide. Each pulse has a soliton-like shape with additional stochastic noise:

$$A(t,0) = A_{sol}(t,0) + \delta A(t,0) \quad (2)$$

$$A_{sol}(t,z) = \frac{\sqrt{P_0}}{cosh(t/t_0)} \quad (3)$$

$$<\delta A(t,0)\delta A^*(t',0)> = \frac{\hbar\omega_0}{2}\delta(t-t') \quad (4)$$

P_0 is the peak power of the soliton-like pulse, t_0 is related to T_{FWHM} as $T_{FWHM} = 2\ln(1+2^{1/2})t_0 \approx 1.763t_0$ [7]. For this pair of pulses we simulate their evolution through the fibre and then calculate Stokes parameters S_0, S_1, S_2, and S_3, which serve as coordinates for a point on a Poincare sphere [2]:

$$S_0(z) = \int dt\left(A_x^*(t,z)A_x(t,z) + A_y^*(t,z)A_y(t,z)\right) \quad (5)$$

$$S_1(z) = \int dt\left(A_x^*(t,z)A_x(t,z) - A_y^*(t,z)A_y(t,z)\right) \quad (6)$$

$$S_2(z) = \int dt\left(A_x^*(t,z)A_y(t,z) + A_y^*(t,z)A_x(t,z)\right) \quad (7)$$

$$S_3(z) = i\int dt\left(A_y^*(t,z)A_x(t,z) - A_x^*(t,z)A_y(t,z)\right) \quad (8)$$

To model the evolution of the Wigner distribution, we simulate the propagation of a multitude of pairs of pulses, which generates a set of points that form a cloud in the S_1S_2 plane. Based on this data, we can calculate the squeezing achieved in the current pulse by finding the angle θ for which the value

$$V = 10\cdot\log_{10}\left(\frac{\left(\frac{1}{\hbar\omega_0}\right)^2<\left(S_1\cos(\theta)+S_2\sin(\theta)\right)^2> - \left(\frac{1}{\hbar\omega_0}\right)^2<\left(S_1\cos(\theta)+S_2\sin(\theta)\right)>^2 - \frac{M}{2}}{\left(\frac{1}{\hbar\omega_0}\right)<S_0>-M}\right) \qquad (9)$$

This research was funded in part by the Russian Foundation for Basic Research, Grant No. 19-29-11032 (Analytical estimates), and in part by the Mega-grant of the Ministry of Science and Higher Education of the Russian Federation, Contract No. 075-15-2021-633 (Numerical simulations).

is minimal [2].

We compare the value of squeezing V calculated for different pulse durations T_{FWHM} and pump powers P_{pump}, which relate to the peak power P_0 as $P_0 = \frac{P_{pump}}{4t_0\nu_{rep}}$, where ν_{rep} is the repetition rate of the laser that is used in the squeezing experiment. We also compare the results with analytical formula

$$V_0 = 10 \cdot log_{10}(1 - 2r_{Kerr}\sqrt{1 + r_{Kerr}^2} + 2r_{Kerr}^2), \quad (10)$$

which is applicable for squeezing of CW light, where the $r_{\text{Kerr}} = \gamma P \cdot z$ is the Kerr parameter, P is CW light power. While this formula is not directly applicable to pulses, it may serve as the useful upper-bound for squeezing [8]:

We do calculations based on the real experimental polarization squeezing setup. In this setup, $\gamma = 2.25$ $(\text{W}\cdot\text{km})^{-1}$, and $\beta_2 = -10.5$ ps^2/km. We also set fibre loss to be 1.8 dB/km, $\lambda = 1.55$ µm, repetition rate of 80 MHz and temperature of 300 K. Pulse widths vary from 0.235 ps to 0.385 ps, pump powers are in the 10-16 mW region, which corresponds to peak powers close to that of fundamental soliton with these parameters. The setup is assumed to have R=20% accumulated loss over the course of propagation in optical elements. To consider the influence of these losses, we apply the known formula for squeezing reduction due to losses: [8]:

$$V_{loss} = 10 \cdot \log_{10}[(1 - R)10^{V/10} + R] \quad (11)$$

III. Results

The resulting polarization squeezing for soliton-like pulses produced by simulation and the upper-bound estimation provided by formula are shown in Fig. 1. Due to shorter waveguide lengths, Raman effects are not prevalent in the fibre. Because of this, squeezing increases as we raise the power of the pulse. When we increase the duration of the pulse while maintaining its energy, the peak power decreases, thus the squeezing decreases as well. The squeezing calculated by the analytical formula has the same behavior. However, while it also predicts stronger squeezing than the simulation for all kinds of pulses, the drop-off in squeezing as we increase the duration of the pulse is sharper in the simulation. This happens due to analytical estimations used being based on the CW signal – it works better for pulses that have their energy concentrated in a small period of time and which don't experience any notable Kerr effect outside of it, thus longer duration pulses diverge more from the estimate. The noise suppression calculated is in the -6 - -12 dB region without accounting for experimental losses occurring in the setup. If we take those into account, the setup can provide squeezing of around -5 dB.

In conclusion, we analyzed the behavior of quantum noise squeezing for pulses of various parameters using numerical simulation, discovered the dependencies of quantum noise suppression on the width and energy of the pulse, and demonstrated that for typical experimental lengths of fibre, squeezing in higher-energy pulses with shorter duration can reach up to -12 dB.

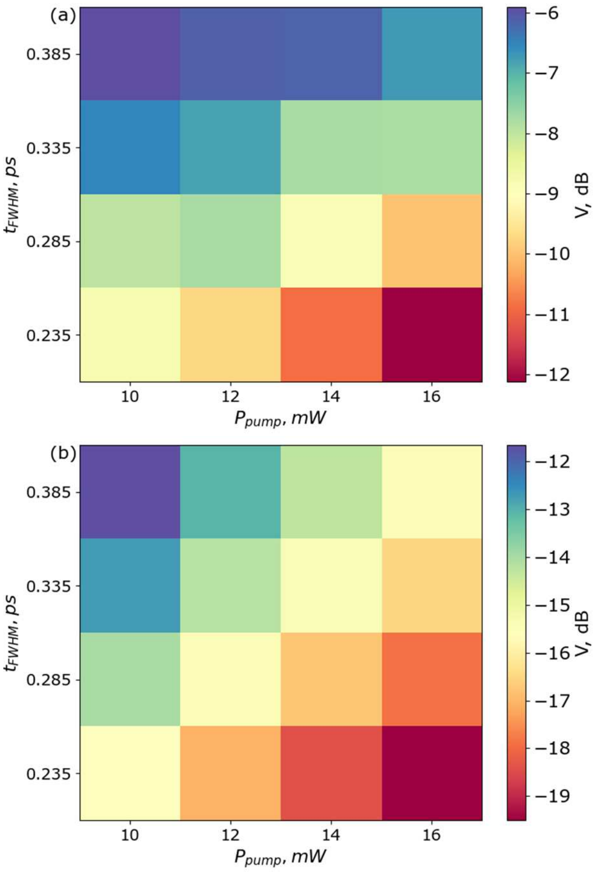

Fig. 1. The dependency of Kerr squeezing of soliton-like pulses of light at the end of the fiber on their energy and duration: numerically simulated by means of the full quantum model in (a) and by use of CW approximation formula in (b).

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