Numerical Simulations on Quantum Noise Squeezing for CW Light in Highly Nonlinear Tellurite Fibers

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Abstract — **Quantum noise suppression of light is desirable for a lot of applications including quantum communication, quantum sensing, and detection of gravitational waves. There are several ways to obtain squeezed light including Kerr squeezing in optical fibers. Silica fibers are commonly used for this purpose. Here we propose to use highly nonlinear tellurite glass fibers for Kerr squeezing of CW light and demonstrate by quantum dynamical simulations the possibility of -20 dB noise suppression. To simulate CW light evolution with allowance for the quantum noise using the Wigner representation, we used the Raman-modified stochastic nonlinear Schrödinger equation. We take into account group velocity dispersion, deterministic nonlinear response including Kerr and Raman contributions, linear quantum noise, Raman noise, and optical losses. In simulations, Raman effects and losses are switched on and switched off to find their contributions to the limits of squeezing. For the optimal fiber lengths, losses limit the noise suppression.**

I. Introduction

Quantum noise suppression of light is desirable for a lot of applications including quantum communication, quantum sensing, and detection of gravitational waves [1]. For example, the 1st long-term application of quantum squeezed light for a gravitational-wave observatory was demonstrated in [2]. In novel detectors of gravitational waves, the injection of -10 dB quantum squeezed light is required and investigations in this direction are in progress. Squeezed light is a quantum state with a variance of one field quadrature being below the value for a coherent or a vacuum state (whereas the conjugated quadrature variance is above the variance of the vacuum in order to satisfy Heisenberg's uncertainty relation). There are several ways to obtain squeezed light including Kerr squeezing in optical fibers [1]. Optical fibers based on silica glass were used in corresponding experiments [1,3]. However, there are other glass fibers with a large Kerr nonlinearity, which may have certain advantages for quantum noise suppression. Chalcogenide glass [4-6] and tellurite glass [7-10] fiber-based devices are widely used for a nonlinear optical conversion, but barely studied for quantum noise suppression. However, chalcogenide fibers with large nonlinearity and acceptable losses (a few tens of dB/km) were recently proposed and investigated theoretically for Kerr squeezing of CW light [11]. It was shown that quantum noise squeezing stronger than -10 dB can be achieved in a few meters of optimized As_2S_3 or As_2Se_3 glass fibers [11]. Here we propose to use highly nonlinear tellurite glass fibers based on TeO_2 and demonstrate their huge potential for Kerr squeezing of CW light (down to -20 dB) by performing quantum dynamical simulations, for the first time, to the best of our knowledge.

II. Concept of Using Highly Nonlinear Tellurite Glass Fibers for Quantum Noise Squeezing

Tellurium dioxide (TeO_2) based glasses possess the merits of sufficient chemical stability, wide transparency range up to ~5 μm, and large linear (n ≈ 2) and nonlinear (~20-30 times higher than for silica) refractive indices. Many tellurite glass compositions are stabile against crystallization. Current technologies make it possible to produce low-loss (~20 dB/km at 1.55 μm) tellurite glass fibers [8]. Optical fibers with a small core size produced from tellurite glasses can have nonlinear Kerr coefficient γ 2-3 orders of magnitude higher than standard telecommunication fiber SMF28e, for which $\gamma \approx 1$ $(\mathrm{W\ km})^{-1}$ [10]. Based on the large Kerr nonlinearity and relatively low optical losses, we propose to use tellurite fibers for CW light quantum noise squeezing at a wavelength $\lambda = 1.55$ μm corresponding to available quantum noise limited laser sources. Optimal lengths of tellurite fibers should be significantly shorter than optimal lengths of silica fibers for observation of equivalent Kerr phase shift and achievement of strong squeezing. It should be noted that short fiber lengths (of about a few meters for tellurite fibers) are advantageous for suppressing guided acoustic wave Brillouin scattering (GAWBS), because noise introduced by GAWBS depends linearly on the fiber length.

III. Numerical Model

To simulate the CW light evolution with allowance for the quantum noise using the Wigner representation, we use the Raman-modified stochastic nonlinear Schrödinger equation [12,13]:

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

where A is the complex amplitude, t is time, z is the coordinate along the fiber, γ is the nonlinear Kerr coefficient, α is optical loss, β_2 is the group velocity dispersion, $R(t)$ is deterministic nonlinear response including Kerr and Raman contributions, Γ and Γ^R describe linear quantum noise and Raman noise, respectively. Γ and Γ^R are zero-mean delta-correlated random values with normal distribution in the frequency domain [12,13]. We used the same equation and specially developed numerical code based on the split-step Fourier method for modeling of Kerr noise squeezing of optical solitons in silica fibers [13]. For tellurite glasses, the nonlinear response function $R(t)$ differs from the Raman response function for the silica glass. He we use the approximation of the Raman response for tellurite glass from [9]. GAWBS is neglected due to relatively short fiber length of about a few meters. In simulations, Raman effects and losses are switched on and switched off to find their contributions to the limits of quantum noise squeezing.

We simulated propagation of light with 1000 independent noise realizations through a certain fiber length, and based on these data we calculated the quantum fluctuations of one of the quadrature components of the signal rotated at the optimal angle in the phase space.

For comparison, we also analytically estimate squeezing for CW light without Raman effects, which is given under the lossless approximation by the following expression [14]:

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

here $r_{\mathrm{Kerr}} = \gamma P\cdot z$ is the Kerr parameter, P is CW light power. It is known that if the squeezed light propagates through an element with a loss coefficient $R = 1\text{-}10^{-\chi/10}$, where χ is a lumped loss in dB, squeezing is reduced to [14]:

$$V_{loss} = 10\cdot\log_{10}[(1-R)10^{V/10}+R] \tag{3}$$

We take fiber loss of 20 dB/km as in [8] and based on known refractive indices and geometrical size of the reported tellurite fiber [8], calculate γ = 300 (W·km)$^{-1}$ and β_2 = 200 ps^2/km. We also set P = 10 W, λ = 1.55 μm, and temperature of 300 K.

IV. Results

The numerically simulated and analytically estimated results of quantum noise squeezing in highly nonlinear tellurite fibers are presented in Fig. 1. As expected, the analytical estimate without Raman effects and loss gives the strongest Kerr squeezing which monotonically improved for longer fibers. The optical loss and Raman effects lead to squeezing reduction. For fiber lengths shorter than 5 m, the Raman effects are not important, but for longer fibers, the Raman nonlinearity significantly limits noise suppression. The comparison between a simple approximation of loss lumped at the fiber output and full modeling with loss distributed along the fiber shows that approximation predicts smaller absolute values of optimal squeezing. This may be explained as follows. The effect of distributed losses along with simple gradual reduction of the light power manifests itself in addition of some vacuum noise along the propagation distance. The noise added at the initial propagation stage gets squeezed in the subsequent fiber pieces. In contrast, approximation given by (3) applies the effect of losses at the output, so that it is not affected by nonlinear propagation.

In conclusion, we proposed to use highly nonlinear tellurite glass fibers for Kerr squeezing of CW light and demonstrate by quantum dynamical simulations their great potential. The possibility of -20 dB noise suppression of CW light is attained for a wide range of tellurite fiber lengths of 2-5 m (Fig. 1). For fibers with lengths >5 m, the Raman threshold is exceeded significantly and the Raman effects quickly deteriorate the quantum noise suppression.

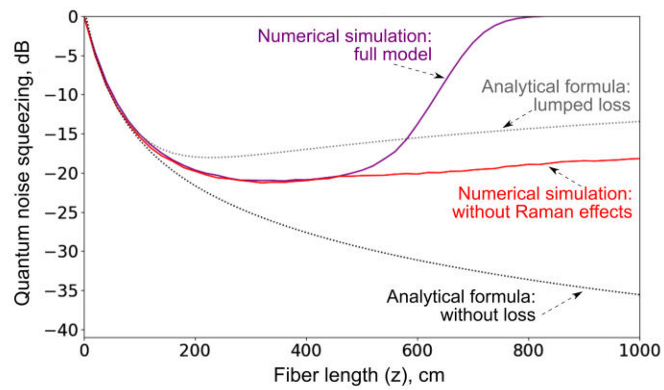

Fig. 1. Kerr squeezing of CW light in tellurite fibers: numerically simulated in the framework of the full model described by Eq. (1); numerically simulated in the framework of Eq. (1) without Raman effects; analytically estimated without loss and Raman effects using formula (2); and analytically estimated with lumped loss using formula (3).

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