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Microarticle

Quantum noise squeezing of CW light in tellurite glass fibres

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ABSTRACT

Light with suppressed quantum fluctuations is desirable for a lot of applications. There are several approaches to suppress a noise including Kerr squeezing in optical fibres. Silica fibres are commonly used for this purpose. Here we propose to use highly nonlinear tellurite glass fibres for Kerr squeezing of CW laser field and demonstrate by simulations in the framework of the stochastic generalized nonlinear Schrödinger equation the possibility of –20 dB noise suppression. In simulations, Raman terms and losses are switched on and switched off to find their contributions to the limits of squeezing. The analytical estimates without loss and with lumped loss are also given.

Introduction

Light with suppressed quantum fluctuations is desirable for different applications including quantum metrology, quantum networking, and gravitational wave detection [1]. The 1st long-term application of light with suppressed quantum noise for gravitational wave detection was presented in [2]. In new detectors, the use of –10 dB quantum squeezed light is demanded. This is a strong motivation for the development of such light sources. Squeezed light is a quantum state with a variance of one quadrature smaller than the value for a coherent state (but the variance of the conjugated quadrature is larger for satisfying Heisenberg's uncertainty relation). There are several approaches to suppress quantum noise including Kerr squeezing in optical fibres [1]. Using Kerr nonlinearity, it is possible to squeeze the quantum fluctuations of one of the field quadrature components, rotated at a specific angle φ in the phase space, while the variance of the other component grows (Fig. 1 (a)). Optical fibres based on silica glasses were commonly used in corresponding experiments [1,3]. However, there are other glass fibres with a large Kerr nonlinearity, which may have certain advantages for noise suppression. Chalcogenide and tellurite glass fibres are widely used for nonlinear optical conversions [4–6], but barely studied for quantum noise squeezing. However, chalcogenide fibres with large Kerr nonlinearity and acceptable losses (a few tens of dB/km) were recently proposed and investigated theoretically for squeezing of light [7]. It was shown that suppression of quantum fluctuations stronger than –10 dB can be achieved in a few meters of optimized chalcogenide As_2Se_3 or As_2S_3 glass fibres [7]. Here we propose to use highly nonlinear tellurite glass fibres (based on TeO_2) and demonstrate their great potential for Kerr squeezing (down to –20 dB) by performing quantum dynamical simulations of CW laser field evolution in tellurite fibres with real parameters.

Concept of using tellurite glass fibres for suppression of quantum fluctuations

Tellurite glasses have large nonlinear refractive index n_2 (~20–30 times higher compared to silica) [4]. Many tellurite glass compositions are stabile against crystallization and possess an excellent chemical stability [4]. Existing technologies allow manufacturing low-loss (~20 dB/km at $\lambda = 1.55$ μm) tellurite glass fibres [5]. Optical fibres with a small core size having a small mode field area A_{eff} produced from tellurite glasses can have nonlinear Kerr coefficient $\gamma = 2\pi n_2/(\lambda A_{\text{eff}})$ 2–3 orders of magnitude higher compared to telecom fibre SMF28e with $\gamma \approx 1$ (W km)$^{-1}$. Based on a large Kerr nonlinearity and relatively low optical losses, we propose to use tellurite fibres for suppression of quantum fluctuations of CW laser field at a wavelength $\lambda = 1.55$ μm corresponding to available quantum noise limited laser sources. Optimal lengths of tellurite fibres should be significantly shorter than optimal lengths of silica fibres for observation of equivalent Kerr phase shift and achievement of strong squeezing. It should be noted that short fibre lengths (of about a few meters for tellurite fibres) are advantageous for suppressing GAWBS (guided acoustic wave Brillouin scattering), because noise introduced by GAWBS depends linearly on the fibre length.

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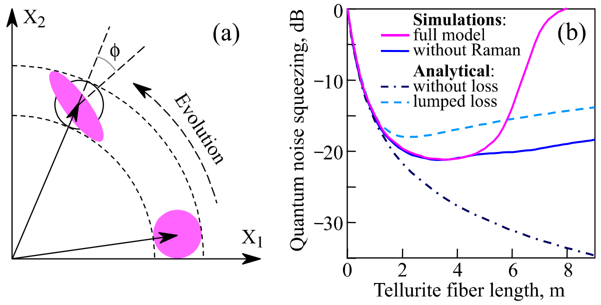

Fig. 1. (a) Quantum noise squeezing of a coherent state in quadrature phase space due to Kerr nonlinearity. (b) Quantum noise squeezing of CW laser field in tellurite fibres: numerical *simulations* in the framework of the *full model* described by Eq. (1) (solid magenta line); numerical simulations in the framework of Eq. (1) *without Raman* terms (solid blue line); *analytical* estimate *without loss* using formula (2) (dash-dotted line); and analytical estimate with *lumped loss* using formula (3) (dashed line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Methods

To simulate the CW laser field evolution with allowance for the quantum noise using the Wigner representation, we use the stochastic generalized nonlinear Schrödinger equation [3,8]:

$$\frac{\partial A(t,z)}{\partial z} = + \left[i\gamma \int_0^\infty R(t-s)|A(s,z)|^2 ds + \Gamma^R(t,z) \right] A(t,z) - \alpha A(t,z) + \Gamma(t,z) + i\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2}A(t,z) \tag{1}$$

where A is the complex amplitude of the laser field, t is time, z is the coordinate along the tellurite fibre, α is optical loss, β_2 is the 2nd-order 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 [8]. We used the same equation and specially developed numerical code based on the split-step Fourier method for modeling of Kerr noise squeezing of solitonic pulses in silica fibres [8]. For tellurite glasses, the nonlinear response function $R(t)$ differs from the Raman response function for the silica glass. Here we use the approximation of the Raman response for tellurite glass from [6]. GAWBS is neglected due to relatively short fibre length of about a few meters. In simulations, Raman terms and losses are switched on and switched off to find their contributions to the limit of suppression of quantum fluctuations. We simulate propagation of light with 10^3 independent noise realizations through a certain tellurite fibre length, and based on these data we calculate the quantum fluctuations of one of the quadrature components of the signal rotated at the optimal angle in the phase space (Fig. 1(a)). For comparison, we also analytically estimate squeezing for CW laser field without Raman and loss terms (V) and with lumped loss (V_{loss}) [8]:

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

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

here $r_{\text{Kerr}} = \gamma P z$ is the Kerr parameter, P is power, R is a loss coefficient: $R = 1{-}10^{-\zeta/10}$, and ζ [in dB] is a lumped loss.

We take fibre loss of 20 dB/km as in [5] and based on the reported tellurite fibre parameters [5], calculate $\gamma = 300$ (W•km)$^{-1}$ and $\beta_2 = 200$ ps^2/km. We also set $P = 10$ W, $\lambda = 1.55$ μm, and temperature of 300 K.

Results and conclusions

The numerically simulated and analytically estimated results of quantum noise squeezing in highly nonlinear tellurite fibres are presented in Fig. 1(b). As expected, the analytical estimate by expression (2) without Raman terms and loss gives the strongest suppression of fluctuations which monotonically improved for longer fibres. The optical loss and Raman terms lead to squeezing reduction. For $z < 5$ m, the Raman terms are not important, but for longer fibres, the Raman nonlinearity significantly limits noise suppression. Analytical formula (3) predicts smaller absolute values of optimal squeezing compared to full modeling with distributed losses. The explanation is following. The quantum effect of distributed losses can be interpreted as addition of vacuum noise along the fibre (classical decrease of power does not make a noticeable contribution). The noise added at the early evolution stage is squeezed in a successive fibre piece. In contrast, formula (3) applies the loss at the fibre output, so that it is not influenced by nonlinear evolution. The possibility of –20 dB noise suppression of CW light is attained for a wide range of tellurite fibre lengths of 2–5 m (Fig. 1). For fibres with lengths >5 m, the Raman threshold is exceeded significantly and the Raman terms quickly deteriorate suppression of quantum fluctuations. Thus, the proposed highly nonlinear tellurite fibres for Kerr squeezing of CW laser field demonstrate a great potential.

CRediT authorship contribution statement

E.A. Anashkina: Conceptualization, Methodology, Investigation, Writing - original draft. **A.A. Sorokin:** Investigation, Software. **G. Leuchs:** Conceptualization, Funding acquisition. **A.V. Andrianov:** Conceptualization, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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