Simulations of polarization squeezing of ultrashort pulses in fibres

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Polarisation squeezing in optical fibres can efficiently produce highly squeezed light[1]. Because the experiments operate in a very nonclassical regime, the results are very sensitive to additional nonlinear and thermal effects in the fibre. To quantitatively characterise such experiments, we perform first-principles, quantum dynamical simulations of intense, ultrashort pulses in a fibre, including all significant quantum and thermal noise. We compare simulation and experiments to find excellent agreement over a wide range of pulse energies and fibre lengths. From the simulations, we can identify the particular noise sources that are the limiting factors at high and low input energy.

In the experiment, two identical pulses propagate along orthogonal polarisation axes of a polarisation-maintaining fibre. The emergent, squeezed pulses have same intensity, temporal overlap and π/2 phase shift (via a feedback loop). The pulses are combined on a half-wave plate and the squeezing measured at a frequency of 17.5MHz, to avoid technical noise. Most of the excess noise induced by the fibre is common-mode and is thus cancelled.

We use a quantum model of a radiation field propagating along a fibre, including the electronic χ^(3) nonlinear responses of the material and nonresonant coupling to phonons in the silica. The phonons provide a non-Markovian reservoir that generates additional, delayed nonlinearity, as well as spontaneous and thermal noise. The coupling is based on the experimentally determined Raman gain α^R(ω). In all, we have > 10^8 photons in > 10^2 modes, corresponding to an enormous Hilbert space.

To simulate such a system, we use a truncated Wigner technique[2], which provides an accurate simulation of the quantum dynamics for short propagation times and large photon number. Both these conditions are satisfied in the current experiments. The quantum effects enter via initial vacuum noise, which makes the technique ideally suited to squeezing calculations.

Phase-space rotation angle θ, antisqueezing and squeezing for L₁ = 13.4m (red) and L₂ = 30m (blue) fibres. Excess phase noise is determined by a single-parameter fit for each fibre length.

Parameters: t₀ = 74fs, z₀ = 0.52m, T = 2 x 10^8, Eᵣ = 54pJ, λ₀ = 1.51µm

Typical results are shown in the figures, for 13.4m and 30.0 m fibres. The theoretical results for both squeezing and antisqueezing closely match the experimental data, after estimated linear losses of 24% are taken into account. As expected, the level of squeezing generally increases with input power. However Raman effects limit squeezing at very high intensity, and this effect is more pronounced in the longer fibre. The effects of excess phase noise, due to depolarising guided acoustic wave Brillouin scattering (GAWBS), is evident at low pulse energies where the Kerr effect is weaker.

References