

QWE1 Fig. 2. (a) Nonlinear energy transfer function from an asymmetric Sagnac interferometer for 130-fs pulses at a wavelength of 1.51 μm . (b) Photocurrent noise power measured at 20 MHz and normalized to the shot-noise reference level (0dB).

overall detection efficiency of $85 \pm 4\%$. The noise minima in Fig. 2(b) appear at those input energies, where the nonlinear input-output curve, displayed in Fig. 2(a), shows an optical limiting effect. For higher input energies the Raman effect separates the pulses spectrally and temporally and thus leads to a deterioration of the interference contrast of the two counterpropagating pulses, which reduces the squeezing.

The splitting ratio was varied systematically from 97:3 to 53:47 in order to investigate its influence on the optimum squeezing. The experiments showed a drastic increase of excess noise for more symmetric splitting ratios. For example, the noise level increases by more than 24 dB, from -5 dB to $+19$ dB, when changing the splitting ratio from 93:7 to 53:47, although the input energy is adjusted to the optimum optical limiting regime in both cases. This large excess noise reveals a unique feature of the quantum noise behavior.

In contrast to the variation of the splitting ratio an experimental variation of the fiber length is shown to hardly affect the amount of squeezing, provided that a shorter fiber is compensated for by an increased input energy.

The experimental observations are supported by extended numerical simulations, based on a linearization of quantum fluctuations⁶. Those simulations allow for a continuous variation of all parameters and show the overall behavior of the loop. The experimental investigations in combination with the theoretical simulations pave the way towards an optimized quantum soliton source.

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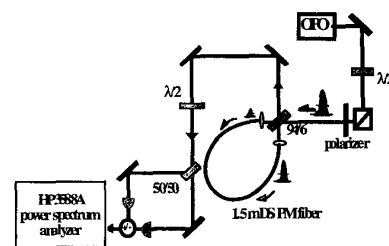
QWE2 2:45 pm
Photon number squeezing in the normal dispersion regime

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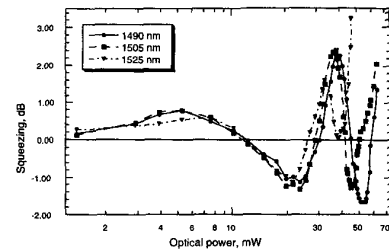
Significant progress has been recently achieved in producing amplitude-squeezed optical soliton pulses in a new experimental scheme. This scheme, originally proposed¹ and later generalized by M.J. Werner,² is based on interference of optical fields and is potentially capable of producing large squeezing levels in excess of 10 dB. In an experimental demonstration of this scheme the authors have recently reported directly observing 5.7-dB (6.2 dB correcting for losses) in the photon-number fluctuations below the shot-noise level with 180-fs, high-energy, soliton pulses centered at 1550 nm in a highly asymmetric Sagnac interferometer geometry.³

Soliton pulses have a distinctive property of acquiring a uniform nonlinear phase shift across the pulse, which provides for the most efficient generation of squeezing. It is, however, not required by the theory to have a soliton pulse in order to observe noise reduction so the practical scope of the squeezing-generating experiments can be significantly expanded. It has been predicted by Werner and Friberg that for optical pulses squeezing can be observed in the normal dispersion regime.⁴ In this paper we experimentally demonstrate this effect in the imbalanced Sagnac loop geometry.

The experimental setup is shown in Fig. 1. A Spectra-Physics Opal laser is used as a source of 120-fs (FWHM) sech-shaped optical pulses at a repetition rate of 82 MHz. We use an asymmetric Sagnac loop configuration in which the light is split by a 94/6 free-space beamsplitter and then coupled from both ends into a 1.5-m section of the dispersion-shifted, polarization-maintaining (DSPM) optical fi-



QWE2 Fig. 1. Experimental setup: OPO, optical parametric oscillator, $\lambda/2$, half-wave plates.



QWE2 Fig. 2. Relative noise power fluctuations vs. the input optical power for 3 different wavelengths.

ber with a 6- μm core diameter and a zero-dispersion point at 1562 nm. The dispersion of this fiber was carefully measured for the range of the relevant wavelengths using a Michelson interferometer set-up.⁵

The two parts of the initial pulse counter-propagate in the fiber and re-interfere at the beamsplitter. The photocurrent fluctuations associated with the resulting pulse are measured by a balanced receiver (Epitaxx ETX-1000T photodiodes) followed by a HP3588A power spectrum analyzer operated in a zero-span regime centered around 5 MHz with the resolution bandwidth of 17 kHz. We use the subtraction mode of the receiver for shot-noise calibrations, and the summing mode is used for direct detection of the amplitude fluctuations.

Several calibrations were performed as described in Ref. 3 to accurately establish the shot-noise and the other relevant noise levels to within 0.1 dB. The experimental results where squeezing was observed are shown in Fig. 2, where the squeezing (noise power normalized to the shot-noise level) is plotted vs. the optical power entering the loop for three different wavelengths of 1490, 1505, and 1525 nm. The dispersion parameter β'' of the fiber was measured for these wavelengths to be 4.85, 3.85, and 2.55 ps^2/km respectively. This figure demonstrates the dependence of squeezing on the dispersion. As the effective length of the fiber changes in terms of the number of dispersion length, we observe the change in the location of the squeezing resonances. The largest noise reduction is observed at 1490-nm where we directly measure 1.7 ± 0.1 dB of squeezing. Correcting for linear losses, this corresponds to 2.5 ± 0.2 dB of squeezing.

In conclusion we have experimentally demonstrated a practical possibility of producing amplitude-squeezed light in a non-soliton regime and measured 1.7 ± 0.1 dB (2.5 ± 0.2 dB correcting for losses).

1. M.J. Werner, in *Symposium on Quantum Optics for Communications*, OSA Annual Meeting, Long Beach, 1997 (OSA, Washington, DC, 1997).
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