Amplitude squeezing of light by means of a phase-sensitive fiber parametric amplifier

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We experimentally demonstrate generation of bright sub-Poissonian light by means of parametric deamplification in a phase-sensitive fiber amplifier that is based on a balanced nonlinear Sagnac interferometer. On direct detection, the photocurrent noise falls below the shot-noise limit by (0.6 ± 0.2) dB (1.4 dB when corrected for detection losses). To observe the noise reduction we employed a scheme that used two orthogonally polarized pulses to cancel the noise that arises from the predominantly polarized guided-acoustic-wave Brillouin scattering in the fiber. We also present a simplified semiclassical theory of quantum-noise suppression by this amplifier, which is found to be in good agreement with the experimental results. © 1999 Optical Society of America

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Recently, bright sub-Poissonian solitonlike pulses of light were predicted[1] and obtained[2] from an unbalanced nonlinear Sagnac interferometer. The mechanism of noise reduction was explained from soliton perturbation theory.[3] The success of such experiments critically depends on the use of ultrashort (femtosecond) pulses that allow substantial nonlinear phase shifts to be achieved in short (a few meters) lengths of fiber. For picosecond pulses, however, the required longer fiber lengths lead to accumulation of excess noise that is due to scattering on thermally excited acoustic modes of glass fiber, also known as guided-acoustic-wave Brillouin scattering (GAWBS),[4] which makes observation of quantum effects difficult. Although it is possible to observe squeezing in a narrow band of frequencies with use of a very high-repetition-rate laser,[5] two schemes were developed for broadband suppression of the GAWBS noise in experiments that employed a balanced Sagnac interferometer: (i) cooling the fiber to liquid-nitrogen temperatures[6] and (ii) generating two squeezed-vacuum pulses, separated by a short time delay, and detecting them with a relative phase shift of π by use of a two-pulse local oscillator.[7] To achieve cancellation of excess noise, the second method needed time delays shorter than the inverse bandwidth of GAWBS, which required a gigahertz electro-optic modulator for fast phase switching.

In this Letter we report the generation of bright sub-Poissonian light from a balanced nonlinear Sagnac interferometer and, in the process, demonstrate a different method of GAWBS compensation, which does not rely on ultrafast electronics for phase switching and synchronization. Instead, we use two orthogonally polarized pulses to cancel the noise that is due to GAWBS, which is predominantly of the same polarization as the input signal. Furthermore, in contrast to the previous research, wherein a balanced Sagnac loop was used for quadrature squeezing of the input vacuum,[5–7] we inject a coherent-state input signal, which can be either amplified or deamplified depending on its phase relative to that of the pump, transforming a balanced Sagnac interferometer into a nonlinear and phase-sensitive amplifier (PSA).[8] In the case of deamplification, the output signal can be shown to be sub-Poissonian, even when the signal power is comparable in magnitude with that of the pump. This makes the quantum-noise reduction robust with respect to the pump leakage into the signal arm.[9]

To obtain an analytical model for the quantum-noise reduction in a Sagnac PSA we developed an intuitive semiclassical approach. It is based on linearization of the classical gain expression[8] for an input signal of power S_{in} in the presence of pump of power P_{in} [i.e., $S_{\text{out}} \equiv G(P_{\text{in}}, S_{\text{in}}, \theta)S_{\text{in}}$]:

$$G = \cos^2(\Phi_x) + (\Phi_p/\Phi_s)\sin^2(\Phi_x) - \sqrt{\Phi_p/\Phi_s}\,\sin(2\Phi_x)\sin\theta\,, \qquad (1)$$

where $\Phi_p \equiv \gamma L P_{\text{in}}$ ($\Phi_s \equiv \gamma L S_{\text{in}}$) is the nonlinear phase shift acquired by the pump (signal) field in an optical fiber of length L, θ is the phase difference between the signal and the pump fields at the input, $\Phi_x \equiv \sqrt{\Phi_p \Phi_s}\cos\theta$ is the nonlinear cross-phase shift, γ is the nonlinear interaction constant, and we have expressed all optical powers in photon-number units. Equation (1) is valid for pulsed coherent light of constant peak power, i.e., square pulses that have pulse widths that are small compared with the propagation time through the fiber loop yet long enough for the effect of group-velocity dispersion inside the fiber to be negligible. The latter requirement guarantees that our PSA is a memoryless device, allowing us to neglect cross correlations between quantum fluctuations at different points of time within the pulse. In addition, our linearization model assumes that the coherent-state pump and signal fields at the input are such that the average number of photons $P_{\text{in}}, S_{\text{in}} \gg 1$. This ensures that the output signal field has a well-defined classical phase. The above conditions, which are all met in our experiment, allow us to include quantum noise in

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our model by associating white zero-mean random processes ΔP_{in} and ΔS_{in} with the mean values P_{in} and S_{in}, respectively, so $\Delta P_{\text{in}} \ll P_{\text{in}}$ and $\Delta S_{\text{in}} \ll S_{\text{in}}$. On the other hand, no assumption regarding the relative values of the pump and signal powers is made.

By linearizing the expression for the output noise around the mean powers, i.e., $\Delta S_{\text{out}} = G\Delta S_{\text{in}} + S_{\text{in}}\Delta G$, we find the following expression for the Fano factor ($F \equiv \langle \Delta^2 S_{\text{out}} \rangle / S_{\text{out}}$) at the output:

$$F = (S_{\text{in}}/G)\langle \Delta^2 G \rangle + \langle \Delta G \Delta S_{\text{in}} \rangle + \langle \Delta S_{\text{in}} \Delta G \rangle + G\,. \quad (2)$$

Note here that if G in Eq. (2) is unperturbed or is highly insensitive to the presence of quantum noise at the input (i.e., $\Delta G \approx 0$), then $F = G$, $\forall\,\theta$. This simple result is generally true when Φ_p, $\Phi_s \ll 1$. By linearizing the power-gain fluctuations about the same mean values (i.e., $\Delta G = f_p \Delta\Phi_p + f_s \Delta\Phi_s + f_\theta \Delta\theta$, where $f_p \equiv \partial G/\partial \Phi_p$, $f_s \equiv \partial G/\partial \Phi_s$, and $f_\theta \equiv \partial G/\partial \theta$), we evaluated the second-order correlations that are present in Eq. (2). Special care must be taken in evaluation of these correlations because some of the terms contain the phase noise of the input field that results from the fundamental vacuum fluctuations. In the linearization approximation, $\langle \Delta S_{\text{in}} \Delta\theta \rangle = \langle \Delta\theta \Delta S_{\text{in}} \rangle^* = i/2$ and $\langle \Delta^2 \theta \rangle = (4S_{\text{in}})^{-1} + (4P_{\text{in}})^{-1}$. The result is

$$F = \frac{\Phi_s \Phi_p}{G} {f_p}^2 + \frac{{\Phi_s}^2}{G}\left(\frac{G}{\Phi_s} + f_s\right)^2 + \frac{1}{4G}\left(1 + \frac{\Phi_s}{\Phi_p}\right){f_\theta}^2. \quad (3)$$

Equation (3) is plotted in Fig. 1 with θ chosen such that the resultant Fano factor $F_{\min}$ is at its minimum (best noise reduction). The minimum values of the average power gain $G_{\min}$ are also shown for comparison. It is clear from Fig. 1 that, for most practical values of Φ_p and Φ_s, $F_{\min} \approx G_{\min}$, even though $F \neq G$ in most of these cases for arbitrary values of θ. Also note that the noise suppression improves with larger signal powers, even when the signal and the pump powers are comparable in magnitude, in the region where $\Phi_p > 1$. The penalty, however, is that the value of $F_{\min}$ becomes more sensitive to θ.

The experimental setup is shown in Fig. 2. A 100-MHz train of 7.3-ps sech-shaped pulses from a mode-locked KCl color-center laser, operated at a center wavelength of 1.55 μm, is divided between the signal and the pump arms. Our Sagnac loop is made with 100 m of polarization-maintaining (PM) fiber (Corning SM.15-P). We use two orthogonally polarized pulses in both the pump and the signal arms of the interferometer to cancel the GAWBS noise. A polarization controller in each arm is adjusted to excite both axes of the PM fiber equally. The total signal power in both polarizations at the PSA input is chosen to be ≈3.5 mW, which corresponds to $\Phi_s \approx 0.3$ in either of the two polarization axes. A differential phase controller is adjusted to make the relative phase between the two polarizations in the signal arm differ from that in the pump arm by π. The differential phase adjustment was achieved by precise bending of a piece of the PM fiber oriented with one of its axes along the bending surface. The optical paths of the input signal and the pump pulses are matched for both polarizations. We achieve almost perfect path matching by heating a segment of the fiber while monitoring the PSA again. This ensures that the two signal pulses with orthogonal polarizations that arrive at slightly different times at the input of the Sagnac interferometer are independently deamplified, with the same gain, by the corresponding orthogonally polarized pulses in the pump arm. The output signal pulses, which are separated from the input by a circulator, are directed onto a balanced pair of photodetectors, where the resultant photocurrent noise is measured. Because of the relative π phase shift, the GAWBS-induced noise that results from the cylindrically symmetric acoustic modes is anticorrelated in the two output signal polarizations. Our detectors integrate over the pulses, which are separated in time by ≈170 ps at the output owing to the birefringence of the PM fiber, in the two polarizations, thus canceling the GAWBS noise caused by these modes. Although the excess noise caused by torsional–radial depolarizing modes is not canceled by this scheme, their contribution was shown to be relatively weak.[10]

In Fig. 3(a) we plot the measured relative noise factor F_η (i.e., the power spectral density of the sum

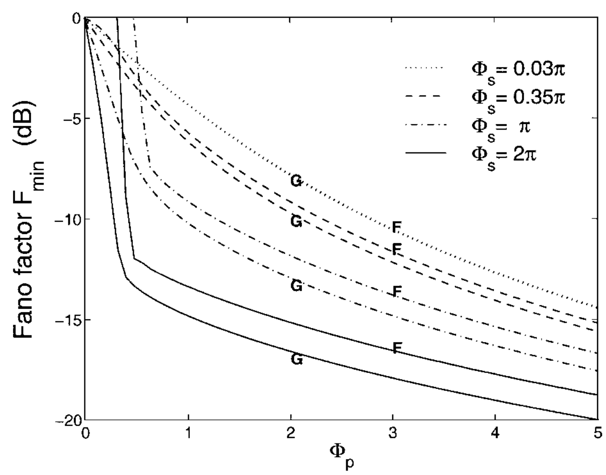

Fig. 1. Minimum Fano factor $F_{\min}$ (F's) and gain $G_{\min}$ (G's) versus Φ_p for four different values of Φ_s.

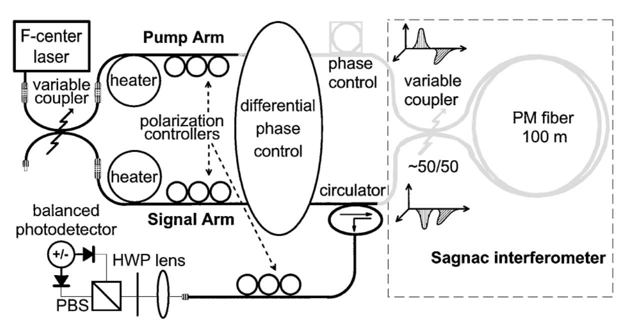

Fig. 2. Experimental setup (the lighter curve indicates PM fiber): PBS, polarizing beam splitter; HWP, half-wave plate.

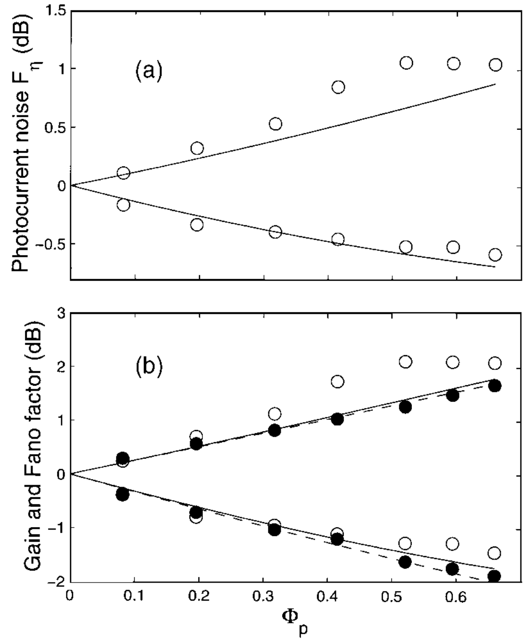

Fig. 3. (a) Amplified (top) and deamplified (bottom) photocurrent noise normalized by the respective shot-noise level (circles, experimental data; solid lines, theory). The experimental data point accuracy is estimated to be within ± 0.2 dB. (b) Fano factors $F_{\min}$ and $F_{\max}$ of the output light (circles, experimental data corrected for $\eta = 0.44$; solid lines, theory) along with the PSA power gains $G_{\min}$ and $G_{\max}$ (filled circles, experimental data; dashed lines, theory).

photocurrent normalized by the corresponding value for the difference photocurrent, the latter representing the shot-noise level) as a function of the pump nonlinear phase shift. We carefully tested our balanced photodetector pair (two Epitaxx ETX500T photodiodes) and the associated electronics to ascertain that the difference photocurrent accurately represents the shot-noise level. The common-mode suppression ratio in the difference photocurrent exceeded 40 dB. The linearity of the photodetector pair and the resultant shot-noise power density were checked over the entire range of our experimental data with the use of a free-space shot-noise-limited laser. The shot-noise level that corresponds to the maximally deamplified signal in our setup was found to be 7 dB above the electronic-noise floor contributed by the power amplifier (Miteq AU-1263, 43-dB gain, 1.6-dB noise figure) following the photodiode pair. The spectral density of the amplified photocurrent noise was recorded at a frequency of 60 MHz by a spectrum analyzer with a 1-MHz resolution bandwidth. A measurement accuracy of 0.1 dB was achieved with use of a 300-Hz video bandwidth. The phase difference between the signal and the pump pulses was adjusted by means of a phase controller (Canadian Instrumentation and Research, Model 915 piezoelectric fiber-stretching device) to produce the minimum and the maximum relative noise factors as the amount of power in the pump arm was varied. As shown in Fig. 3(a), we observed a maximum noise reduction of 0.6 dB $\pm$ 0.2 dB ($F_\eta = 0.87$) below the standard quantum limit. The overall detection efficiency in our setup was measured to be $\eta \approx 0.44$, with the fiber-optic circulator (Optics for Research, Model OC-3-IR2) and the fiber splices accounting for the bulk of the losses. The Fano factors of the deamplified and the amplified light, inferred from the photocurrent noise reduction F_η by correction for $\eta \neq 1$ [i.e., $F = 1 + (F_\eta - 1)/\eta$], are plotted in Fig. 3(b) along with the corresponding measured values of $G_{\min}$ and $G_{\max}$. The minimum Fano factor thus inferred is -1.4 dB.

The predictions of our quasi-cw theory are also shown in Fig. 3 and are found to be in good agreement with the experimental data. We calculated the theoretical curves by integrating the noise and the mean power over the $\text{sech}^2(t)$ pulse profile (quasi-cw approach), which results in $F_{\min} \neq G_{\min}$, in contrast to predictions for square-pulse cases at these power levels. The observed sub-Poissonian behavior, which could not be seen in the absence of the second π-shifted orthogonally polarized pulse, indicates that our scheme to cancel the noise that is due to GAWBS is a practical technique for achieving squeezing in fibers.

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