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# Near-noiseless amplification of light by a phase-sensitive fibre amplifier

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**Abstract.** We report near-noiseless (noise figure of $0.4$ dB, which is an improvement over the theoretical limit of $1.2$ dB for a conventional laser amplifier with the same gain of $1.7$ dB) optical amplification of laser light in a phase-sensitive fibre amplifier.

**Keywords.** Fiber optics, Parametric amplifier, Sagnac interferometer

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A conventional optical amplifier, such as the Er-doped fibre that is in common use in fibre-optic lines, is a type of linear phase-insensitive amplifier (PIA) [1,2]. At optical frequencies the noise contributed by a PIA is mainly determined by the fundamental vacuum fluctuations, which cause random spontaneous emissions of photons by the amplifier, thereby degrading its noise performance. The spontaneous emission noise may be avoided, however, if one employs a linear phase-sensitive amplifier (PSA) [1–3], which is capable of amplifying a signal with a particular optical phase $\theta_{\max}$, whereas the signal with phase $\theta_{\max} + \pi/2$ is deamplified. Such noiseless properties of linear PSAs have recently been verified experimentally using $\chi^{(2)}$-bulk-crystal parametric amplifiers [4,5]. It is also possible to make a pulsed-signal PSA [6–8], based on the $\chi^{(3)}$ nonlinearity of glass fibre by constructing an all-fibre Sagnac interferometer (SI), with gain which can be phase-locked to an incoming signal [9,10]. Fibre-based implementation has practical advantages over the bulk-crystal one, since it can be very compact and reliable. In contrast to our previous work [8] where we employed such fibre PSA to deamplify input signal in order to produce sub-Poissonian light, we investigate the positive gain regime, where fibre PSA is used to boost the signal power. In this paper we demonstrate experimentally the superior noise performance of fibre PSA and prove that our scheme to cancel the excess noise arising from guided-acoustic-wave Brillouin scattering (GAWBS) [11] works well even for the case of light amplification. Such noise cancellation is necessary for any practical fibre PSA designed for use in an optical communication system, since it must be capable of amplifying laser pulses in the frequency range of 0 to 1 GHz where GAWBS exists.

For an amplifier with average power gain $G$ and shot-noise-limited (coherent state) input signal with mean photon number $\langle n_{\rm in}\rangle$, the amplifier's noise figure (NF), which is a function of the mean and the variance of the number of photons in the output, depends on type of the amplifier [2,12]:

$$\langle n_{\rm out}^{\rm PIA}\rangle = G\langle n_{\rm in}\rangle + [G-1], \tag{1}$$

$$\langle \Delta^2 n_{\rm out}^{\rm PIA}\rangle = G(2G-1)\langle n_{\rm in}\rangle + G[G-1], \tag{2}$$

$$\langle n_{\rm out}^{\rm PSA}\rangle = G\langle n_{\rm in}\rangle + \frac{[G+G^{-1}]}{4} - \frac{1}{2}, \qquad (\text{at } \theta_{\rm max}) \tag{3}$$

$$\langle \Delta^2 n_{\rm out}^{\rm PSA}\rangle = G^2\langle n_{\rm in}\rangle + \frac{[G-G^{-1}]^2}{8}, \qquad (\text{at } \theta_{\rm max}) \tag{4}$$

$$\mathrm{NF} \equiv \frac{\mathrm{SNR_{in}}}{\mathrm{SNR_{out}}} \approx \begin{cases} 2-\frac{1}{G} & (\text{for PIA}) \\ 1 & (\text{for PSA}) \end{cases}. \tag{5}$$

Here we have defined the input (output) signal-to-noise ratio as $\mathrm{SNR}_{\rm in(out)} \equiv \langle n_{\rm in(out)}\rangle^2/\langle\Delta^2 n_{\rm in(out)}\rangle$ [i.e., $\mathrm{SNR_{in}} = \mathrm{SNR_{out}}(G=1) = \langle n_{\rm in}\rangle$]. The approximate expression in Eq. (5) reflects a reasonable assumption that $\langle n_{\rm in}\rangle \gg 1$. Thus, the noise figure of a PIA can not be improved beyond the fundamental limit given in Eq. (5), which reaches the value of 2 (i.e., 3 dB) for $G \gg 1$. The PSA, however, is not constrained in this way for any value of $G$ and, in theory, is capable of amplifying signals without introducing any additional noise (i.e., $\mathrm{NF} = 0\,\mathrm{dB}$).

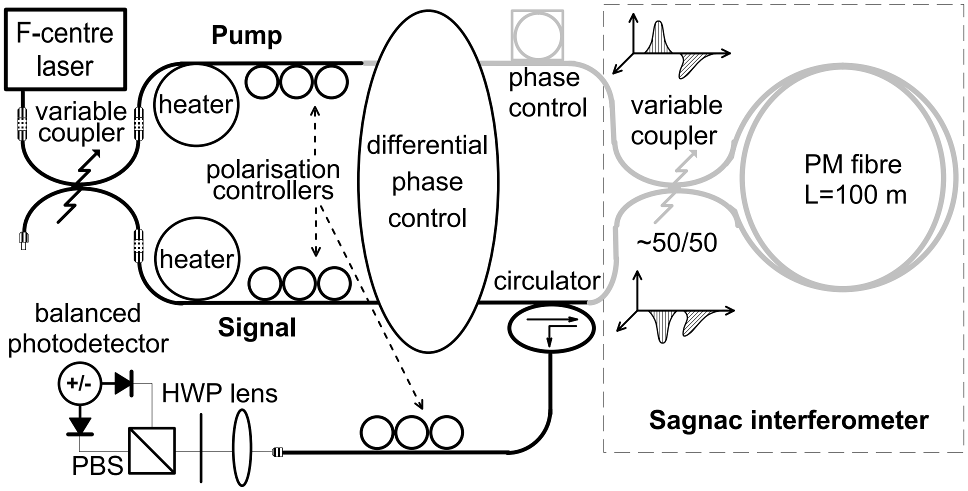

**Figure 1.** Experimental setup (PM fibre shown in gray).

In cases where the effects of group-velocity dispersion can be neglected, the gain of fibre PSA is a nonlinear function of pump and signal powers (see Eq. (1) of Ref. [8]). However,

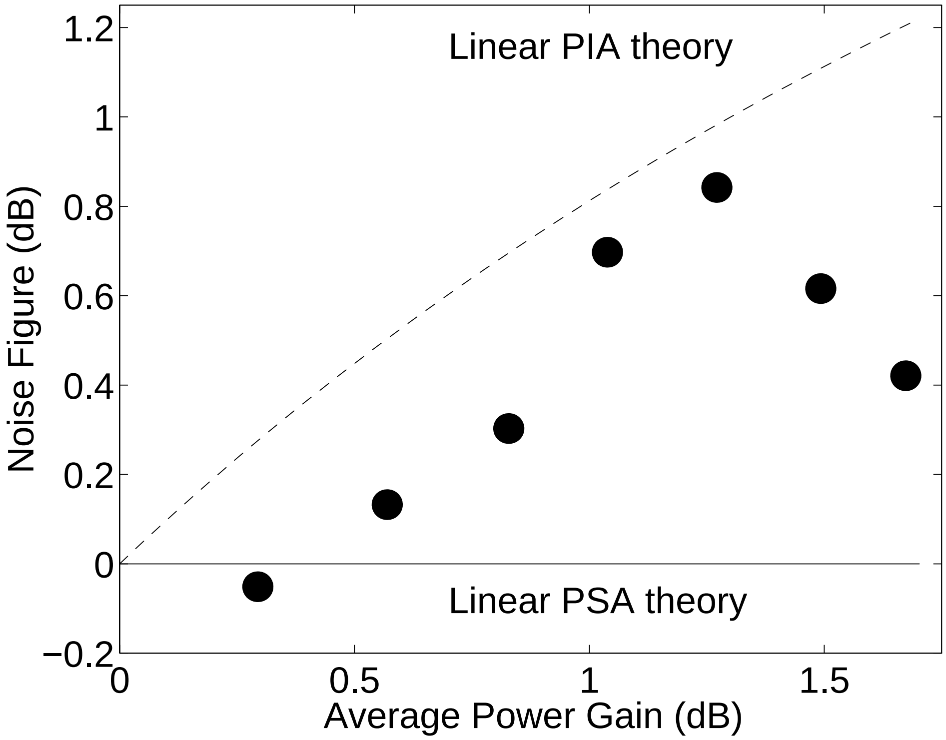

**Figure 2.** Circles – experimental data for the fibre PSA, lines – theory. Deviation from ideal PSA theory is attributed to imperfect GAWBS cancellation, which was more carefully optimized for the last point.

the behavior of the fibre PSA approaches that of the linear PSA when $\Phi_p, \Phi_s \ll 1$ or in the case of large gain:

$$G(\theta_{\max}) \approx \left[\sqrt{1+\frac{\Phi_p^2}{4}}+\frac{\Phi_p}{2}\right]^2 \qquad \text{for} \left\{\begin{array}{c}\Phi_p\Phi_s \ll 1\\ \text{and}\\ \Phi_p/\Phi_s \gg 1\end{array}\right. . \qquad (6)$$

Here $\Phi_p$ ($\Phi_s$) is the nonlinear phase shift acquired by the pump (signal) field in an optical fibre of length $L$, where $L$ is the length of the fibre loop inside the SI.

The parameters of our experimental setup (described in detail in Ref. [8] and shown in Fig. 1), while not strictly conforming to either of the two limiting cases above (pulse-shape averaged $\Phi_s \approx 0.3$, $\Phi_p$ varies from $0$ to $0.7$), nevertheless, allow us to see the improved NF as plotted in Fig. 2. We use a synchronously mode-locked colour-centre laser producing a 100-MHz train of $7.3\,$ps sech-shaped pulses and operating at a centre wavelength of $1.55\,\mu$m. Although in a realistic telecommunication application a PSA would have to use an independent pump source which is phase-locked to the signal, as done in Refs. [9,10], for the purpose of characterization of the PSA noise figure we derive the pump and the signal from the same laser, similar to [6,7,12]. The noise properties of our laser have been carefully studied to insure that it produces a shot-noise-limited light at the measurement frequencies (centered at 60 MHz with a 1 MHz bandwidth). For pulses longer than a few picoseconds, however, the required long fibre length of the SI loop leads to accumulation of classical excess noise arising from GAWBS [11]. We employ two orthogonally-polarised pulses [8] at both the pump and the signal ports of the SI to coherently cancel most of the GAWBS noise. Polarisation controllers at each port are adjusted to equally excite both axes of the PM fibre. The differential phase controller is adjusted to make the relative phase between the two polarisations at the input signal port differ from that at the input pump port by $\pi$ (this makes the contributions of polarised-GAWBS noise anticorrelated in the two signal polarisations at the output), while the phase difference between the signal and pump pulse pairs is scanned by means of a fibre-stretching device. Proper optical path matching (achieved by heating portions of the fibre) insures that the two orthogonally-polarised signal pulses that arrive at slightly different times at the SI's input are independently amplified, with the same gain, by the corresponding orthogonally-polarised pulses of the pump.

The output signal pulses (separated by a circulator) are detected by a balanced pair of photodiodes ($>$40 dB of common mode noise suppression and linearity verified over the entire range of our data), and the difference photocurrent reading is used to establish the shot-noise limit. The sum photocurrent noise is amplified and recorded by a spectrum analyzer with a measurement accuracy of 0.1 dB by using a 300 Hz video bandwidth. Our detectors integrate over the orthogonally-polarised pulses, which are separated by $\approx 170\,\mathrm{ps}$ at the SI's output owing to birefringence of the PM fibre, while canceling most of the GAWBS noise.

The NF in Fig. 2 is inferred from our measurements of the photocurrent noise power and the mean-signal gain after accounting for the non-perfect detection efficiency [12]. The data clearly demonstrates that the noise performance of our fibre-based PSA is superior to that of an ideal PIA, thus proving that GAWBS-compensated fibre PSA can be a viable low-noise alternative to conventional laser amplifiers. Some of the practical issues associated with deploying a PSA in a fibre-optic transmission system, such as achieving high gain and phase-locking an external pump source to the signal, have recently been resolved experimentally [9,10].

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