Phase-Sensitive Optical Pre-Amplifier Implemented in an 80km DQPSK Link

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Abstract: We present the first demonstration of a phase-sensitive fiber optic parametric amplifier successfully implemented over an 80km dispersion managed link. We measure 1.3dB higher sensitivity with this amplifier system against a comparable conventional EDFA-based link.
OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (190.4970) Parametric oscillators and amplifiers

1. Introduction

All commercially available optical amplifiers, utilizing either rare earth doped (e.g. erbium) fibers, III-V semiconductors or stimulated Raman scattering as a source of gain can all be classed as phase insensitive amplifiers (PIAs). Increasing research attention has focused on alternative schemes allowing for phase sensitive amplification (PSA). While PIAs have a well-known quantum limited noise figure (NF) of 3dB, degrading the signal-to-noise ratio with each amplification stage, PSAs can theoretically achieve 0dB NFs, allowing for noiseless amplification [1]. To date, low NF PSAs have utilized parametric amplification to provide gain, in both nonlinear crystals [2] and in fiber optic parametric amplifiers (FOPAs) [3], with FOPA-based PSAs demonstrating much higher gain [4].

One implementation of a FOPA-based PSA utilizes the 'Copier-loss-PSA' architecture. A phase insensitive FOPA (the 'Copier') first creates a phase correlated copy of the signal at the idler wavelength via four-wave mixing (FWM). Signal, idler and pump are then propagated through a lossy element (e.g. a fiber link) before being launched into a second FOPA, which then acts as a PSA. Recently, a proof-of-concept demonstration of a Copier-loss-PSA was shown to increase sensitivity in a model fiber optic link over an erbium-doped fiber amplifier (EDFA) based system [4]. However, in that system the fiber link was emulated by a lumped loss, with the pump wave bypassing the loss.

There are a number of challenges in implementing a Copier-link-PSA, i.e. a Copier-loss-PSA with a long transmission fiber as the loss element. The high power pump wave from the Copier must be heavily attenuated before the fiber link to avoid nonlinear distortion of the co-propagating signal and stimulated Brillouin scattering (SBS), then boosted with minimal distortion to high power for launch into the PSA. The pump, signal and idler, widely spaced in wavelength, must be temporally synchronized after dispersion in the fiber link, and have the same polarization state when launched into the PSA.

Here we present the first demonstration of a Copier-link-PSA, incorporating an 80km span of standard single mode fiber (SSMF), carrying 10GBd quaternary-phase-shift-keyed (QPSK) data. Operating the PSA as a pre-amplifier before an amplified receiver, we measure a marginal (0.2dB) sensitivity penalty operating over a fiber link versus a lumped loss. We compare performance of the Copier-link-PSA-based system against an EDFA amplified link occupying the same bandwidth, showing improved performance in the PSA case.

2. Experiment

In order to characterize the performance of both the PSA and EDFA amplified systems, we place the amplifiers under test directly before a receiver set-up to operated as pre-amplifiers, as illustrated in Fig. 1.

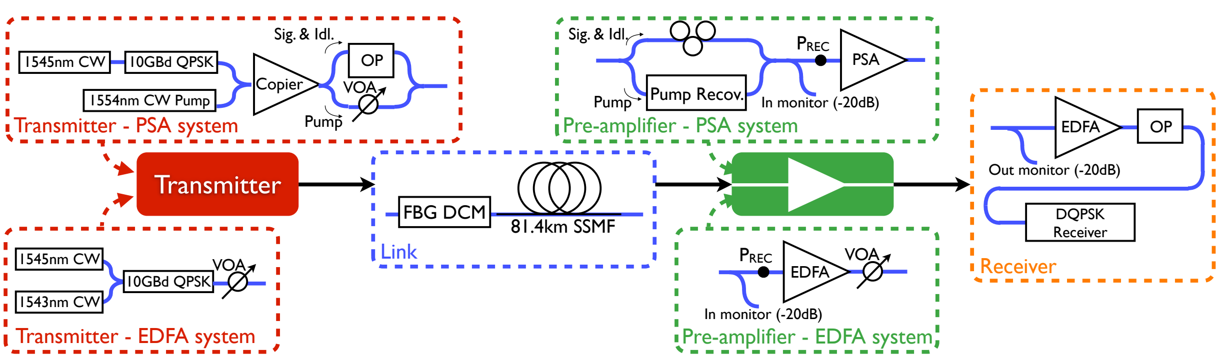

Figure 1: Set-up for both EDFA and FOPA pre-amplifier characterization. OP: Optical processor, VOA: Variable optical attenuator, PC: Polarization controller, FBG DCM: Fiber Bragg grating dispersion compensation module, P_{REC}: Received power measurement point in BER tests.

Previously, the idler wave in a Copier-loss-PSA has been considered an internal mode of the overall amplifier and excluded from estimations of system bandwidth [4]. Here, we consider the Copier as part of the transmitter, and so the occupied bandwidth is twice that of the original signal. As such, to benchmark the performance of the PSA against an EDFA, the EDFA-based system should include two copies of the same signal on separate wavelengths, as illustrated in Fig. 1. These can then be simultaneously detected to artificially increase receiver sensitivity, assuming the channels are spectrally separated by much greater than the receiver bandwidth [5].

The test signal is a 2^{15}-1 pattern length pseudo-random bit sequence (PRBS) 10GBd QPSK data stream at 1545.6nm. The link is dispersion managed, consisting of a fiber Bragg grating dispersion compensation module (FBG DCM, Proximion AB) followed by a 81.4km length of SSMF. The total link loss is approx. 20dB. We measure the received power (P_{REC}) as the power in the 1545.6nm signal channel immediately prior to the pre-amplifier input connector, and the net gain from the signal power before and after the input and output connectors of the pre-amplifier. The receiver in both EDFA and PSA systems is the same, with the exception of the filter central wavelength(s) set in the optical processor (OP, Finisar WaveShaper). The filter profiles used have a flat top pass-band 0.25nm wide. The residual pump from the PSA is removed using a WDM coupler. The signal is differentially detected using a 1-bit delay interferometer and a balanced receiver. For convenience, we vary the received power by attenuating the signal before the fiber link (i.e. in the transmitter blocks, Fig. 1). At the signal launch powers used (<-10dBm) the fiber channel should not provide significant nonlinear distortion. To measure bit-error rate (BER), the pattern analyzer used is encoded with the differential pattern generated from the PRBS sequence.

To minimize residual dispersion in the link, the amount of SSMF was trimmed to temporally synchronize the signal (1545.6nm) and idler (1562.7nm) wavelengths to within ±20ps at the PSA, as measured on a sampling oscilloscope. The OP in the transmitter allowed fine trimming (>±25ps) of relative signal and idler delay [6]. When testing the EDFA, the receiver OP allowed fine trimming. Adjusting the launch polarization into the link minimized the effect of polarization mode dispersion. We aligned the signal and idler, measuring their polarization states at the input of the PSA. The pump was separately aligned after the pump recovery stage. SBS induced by the CW pump in the Copier and PSA FOPAs was reduced by spectrally broadening the pump with sinusoidal phase modulation.

Pump recovery was achieved using a hybrid injection locking/EDFA system, which has been reported at this conference in detail [7]. In brief, the attenuated pump is first amplified by an EDFA, and then passed into a distributed feedback laser diode for injection locking. In this experiment, pump launch power into the link is approx. 10dBm, with about -10dBm entering the pump recovery stage. The injection locking process serves to reduce both amplitude and phase noise from the EDFA, while replicating the SBS suppression tones with high fidelity and boosting pump power to approx. 20dBm. The pump is then boosted by a high power EDFA to 33-34dBm before polarization control and launch into the PSA. The overall effect of pump recovery stage is to provide up to 63dB amplification with negligible distortion of signals parametrically amplified with the recovered pump.

3. Results and Discussion

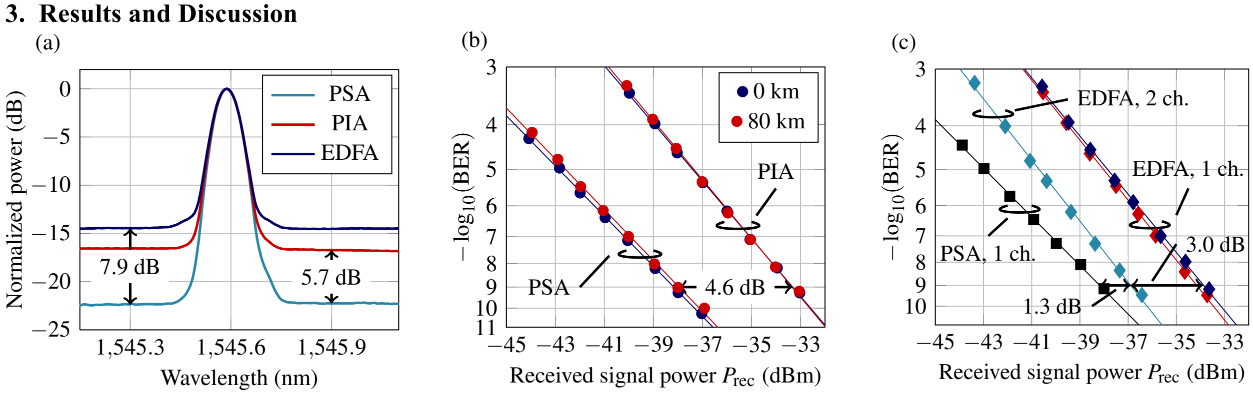

Figure 2: a) Signal spectra out from the pre-amplifiers under test. The spectra (0.1nm resolution) are normalized to their peak values to better compare noise floor levels. b) BER curves comparing FOPA performance with a lumped loss (0km) or fiber link (80km) between copier and PSA. The legend indicates link length used. c) BER curves comparing PSA system performance against the EDFA-based systems. The red and blue EDFA single channel curves correspond to single channel detection of the 1543 and 1545nm wavelengths respectively

Fig. 2a) shows the output spectra with optical noise floors for each of the pre-amplifiers under test. Here net gain is set to 19dB. The FOPA (i.e. PSA in Fig. 1) was switched from PSA to PIA mode by blocking the idler in the OP in the transmitter (Fig. 1), and increasing pump power (generated by the pump recovery stage) to achieve the same net gain. In the EDFA case the unit was run at full pump power and the signal attenuated afterward. Theoretically, PSA mode provides a 6dB signal NF improvement over PIA mode in a Copier-loss-PSA system, reflecting the difference in signal NF between these two amplifier modes [4], close to as shown here. The EDFA shows a higher optical noise floor that the PIA, however, as pump transfer noise in a FOPA does not visibly effect optical spectra [5], this does not necessarily imply that the EDFA has a higher NF. The difficulty quantifying the impact of the various noise contributions in the PSA means the most reliable measure of amplifier performance is gained through BER tests.

We first test to see if the PSA operates well with the fiber link in place, comparing operation in PSA and PIA mode. Fig. 2b) shows BER curves for phase sensitive and phase insensitive FOPA pre-amplifiers, with either a lumped loss or fiber link between the Copier and pre-amplifier. Net gain of the pre-amplifier was set to approx. 19dB. In PIA mode at the error free level ($BER=10^{-9}$), no penalty is observed moving from a lumped loss to fiber link. In PSA mode, a small difference (0.2dB) in received power to achieve error free operation is measured. When comparing PSA and PIA systems, a sensitivity gain of 4.6 and 4.8dB is measured for the fiber link and lumped loss cases respectively, which increases to 5.5 and 5.8dB at $BER=10^{-4}$. From the theoretical 6dB NF improvement, one may infer that the maximum achievable sensitivity improvement between PIA and PSA systems should be 6dB, indicating that the PSA here is not fully optimized.

We then benchmark our PSA against an EDFA. Fig. 2c) compares performance of two systems including PSA and EDFA pre-amplifiers. Net gain in these cases was kept to 25dB. When detecting a single channel in the EDFA-based system, single channel detection in the Copier-link-PSA system is measured to be 4.0-4.3dB more sensitive at $BER=10^{-9}$. When detecting both channels with equal power in the EDFA system, sensitivity is increased by 3dB, as expected. The sensitivity of the EDFA-based system when detecting both channels is 1.3dB less sensitive than the single channel detection Copier-link-PSA system.

There are several practical aspects to consider when comparing these two systems. In the Copier-link-PSA system, the splice losses into the HNLF used in the PSA was 1.1dB (0.2dB is achievable). Optimizing splices should reduce the FOPA (i.e. PSA) noise figure by 0.9dB. However, in these tests, the pump recovery stage was not included as part of the PSA. In the signal path this stage has two WDM couplers and a polarization controller, which have a total insertion loss of 2.6dB in our system, which can be reduced to <0.7dB insertion loss with off-the-shelf components. If both of these factors are optimized, we expect an improved sensitivity in the Copier-link-PSA system of >0.3dB.

Both the EDFA and PSA can be implemented with lower noise figures. The NF of the EDFA is 4.5dB, measured using an OSA. NFs in the range of 3.4dB [8] are realistically achievable for EDFAs. As such, we could realistically expect to achieve 1.1dB greater sensitivity for an optimized EDFA than currently measured with the same transmitter and receiver arrangement. As mentioned, PSA NF may also have further room for optimization.

Moreover, in the Copier-link-PSA system the idler wave is not detected, where as detecting two copies of the same signal in the EDFA-based system increases receiver sensitivity. In the case of phase encoded signals, the idler 'copy' is distorted by the SBS tone modulation, as FWM in the Copier is phase matched when $\phi_{idler}=2\phi_{pump}+\phi_{signal}$, which even when differentially detected significantly distorts the detected idler. Additionally, in our system, we use direct detection and do not assume that forward error correction (FEC) can be applied. If one could use FEC to move the error free threshold to above $BER=10^{-4}$, the sensitivity of the Copier-link-PSA system is increased (by approx.1.4dB) relative to both the single and dual channel detection EDFA-based systems.

4. Conclusion

We have demonstrated the successful implementation of a Copier-link-PSA system over an 80km fiber span, showing minor penalty compared to a system using lumped loss. In a comparison using this PSA as a pre-amplifier before a receiver, we measure a clear sensitivity improvement when compared with an EDFA-based system occupying the same bandwidth. There are several options to increase the fundamental performance of this Copier-link-PSA system, which promises to further improve the achievable sensitivity of optical communication links.

The authors acknowledge Proximion AB for the loan of their FBG DCM module, Lars Grüner-Nielsen of OFS Denmark for the highly nonlinear fiber used in the FOPAs, and Stylianos Sygletos (Tyndall Institute, University College Cork) for the phase locked loop circuit employed in the pump recovery system.

5. References

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