Phase-Sensitive Amplified Optical Link Operating in the Nonlinear Transmission Regime

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Abstract *We characterize a phase-sensitive amplifier (PSA) after an 80km fiber span, carrying a single DQPSK channel in the nonlinear transmission regime. The system penalty with increasing intra-channel nonlinear distortion is similar for EDFA and PSA based systems, indicating that the PSA sensitivity advantage remain with nonlinear transmission.*

Introduction

Phase-sensitive amplification (PSA) has attracted increased research interest over the past few years. Recent demonstrations of optical regenerators for phase encoded signals[1] and low-noise amplification in communication links[2] have highlighted potential applications in fiber optic communications. In particular, PSAs are theoretically limited to a 0dB noise figure (NF)[3], as opposed a 3dB NF for phase-insensitive (PI) amplifiers, such as EDFAs, enabling higher sensitivity in links employing PSAs.

The majority PSAs used for communication experiments utilize four-wave mixing (FWM) in a fiber optic parametric amplifier (FOPA). For a FOPA to demonstrate phase-sensitive (PS) gain, all of the interacting waves in the process are required at its input. One way of achieving this is to utilize two FOPAs in cascade, the first as a PI-FOPA (the 'copier') to effectively generate a phase correlated copy of the signal at the FWM idler wavelength. After passing both signal and idler through a lossy medium (such as a long length of optical fiber), a second FOPA can provide low-noise phase-sensitive amplification[2].

We have recently demonstrated such a cascaded 'copier-PSA' over a single 80km fiber span carrying 10Gbd DQPSK data[4], showing improved sensitivity compared with an EDFA-based system. This sensitivity increase enabled by the low-noise PSA in principle allows for either lower launch power or increased reach between amplification stages. The reach of a single fiber span is limited by sensitivity and nonlinear effects. Sensitivity sets a lower bound on received power, while nonlinear effects in transmission set an upper bound on signal power launched into the fiber link[5]. As such, investigating the nonlinear regime gives insight into the reach limits of our systems. In ref [4], PSA operation in the linear transmission regime was characterized. As low noise PSA relies upon phase correlation between signal and idler, it is not immediately obvious what effect nonlinear phase distortion of the signal and idler in the transmission link between copier and PSA will have on the operation of this type of system.

Here we explore the effects of nonlinear transmission in a PS amplified, 80km long link carrying a single wavelength channel of 10Gbd DQPSK data. We show that the penalty associated with signal self-phase modulation (SPM) is similar for an EDFA-, PI-FOPA- or PSA-based link. By inspecting the constellation diagrams at output from each of these amplifiers, we observe that while phase-sensitive gain modifies the distribution of noise on the signal, no net effect on bit-error rate (BER) is observed. We also measure greater sensitivity for the PSA-based link, over all signal launch powers investigated, than for the EDFA- or PI-FOPA- based link.

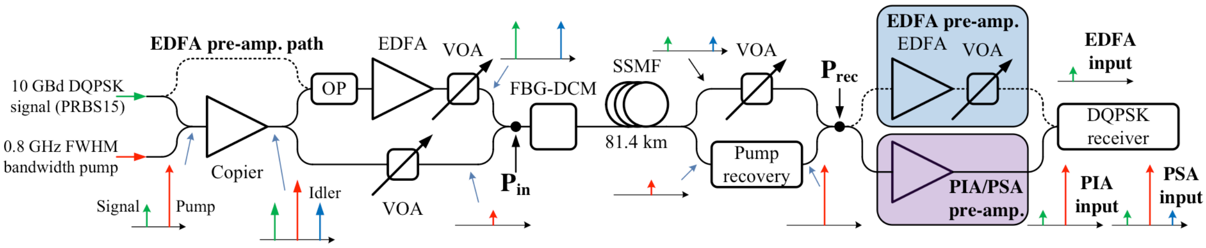

Figure 1. Schematic of experimental set-up. OP – optical processor, VOA - variable optical attenuator, FBG-DCM – fiber Bragg grating dispersion compensation module

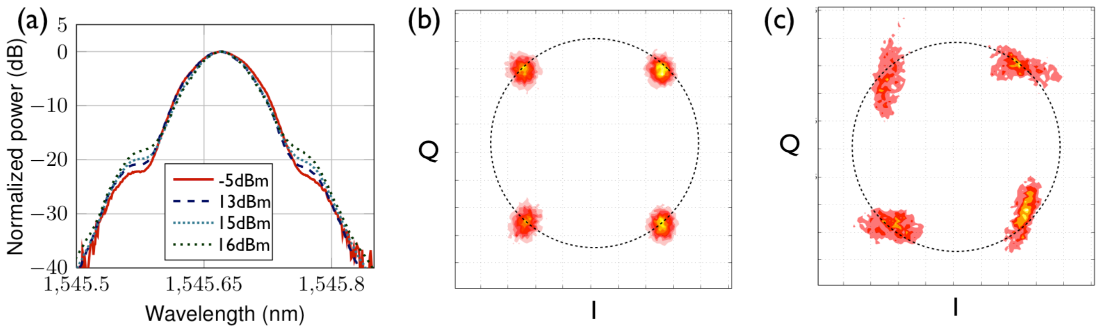

Figure 2. DQPSK signal at output of the 80km link, before the pre-amplifier. a) Optical spectra (legend indicates signal launch power). Constellations are for b) -5dBm and c) +16.5dBm signal launch powers (dashed circles are a guide for the eye).

Experiment

The experimental set-up (Fig. 1) is similar to that used in Ref. [4]. In both the PS- and PI-FOPA systems, the copier generates a phase-correlated idler (at 1562.7nm) before both signal and idler are passed into a booster EDFA to allow access to the nonlinear transmission regime over the link. In the EDFA-based system, the signal bypasses the copier stage and is amplified directly by the booster EDFA. The test signal is DQPSK modulated at 10Gbd, carrying a 2^{15}-1 PRBS at 1545.6nm. The link comprises of a fiber Bragg grating dispersion compensation module before 81.4km of SSMF. The signal is then passed into a pre-amplifier directly before the receiver stage, which is either an EDFA or a FOPA running in PI or PS mode. The signal is then differentially detected using a 1-bit delay interferometer and balanced receiver connected to a BER analyzer.

In order to allow for good operation of the PSA, an optical processor (OP – Finisar WaveShaper) is used to compensate both the uneven gain of the EDFA and residual dispersion of the link. Polarization mode dispersion between signal and idler is minimized by using a polarization controller to couple into the principle states of the link. The strong pump wave from the copier is attenuated to 0dBm before the link, further attenuated by the link loss (20dB), and then recovered using a hybrid EDFA-injection-locking system (reported on in detail in Ref. [6]). Pump power (at 1554.1nm) to the copier is ~38.5dBm and ~33-34dBm to the second FOPA. The pump wave also is sinusoidally modulated to reduce stimulated Brillouin scattering (SBS).

Constellation diagrams of the DQPSK data are generated by a self-homodyne detection system, beating a portion of the signal laser with phase encoded signal, synchronously sampled by a high bandwidth real-time oscilloscope (Tektronix DSA 71604).

Results and Discussion

First, the source of nonlinear signal distortion is investigated. Fig. 2(a) shows normalized optical spectra of the signal at output of the link for various different launch powers. The spectral sidelobes of the data are enhanced with increasing input power, the typical spectral broadening associated with SPM. Fig. 2(b)&(c) show constellation diagrams of the DQPSK data at the end of the fiber link for low (-5dBm) and high (+16dBm) launch powers. The high power constellation shows the 'spiraling' typical of a signal undergoing SPM. Moreover, the back scattered light from the link, monitored through the back reflection port of a 20dB coupler before the link, shows a linear trend rather then the threshold-like behavior associated with SBS.

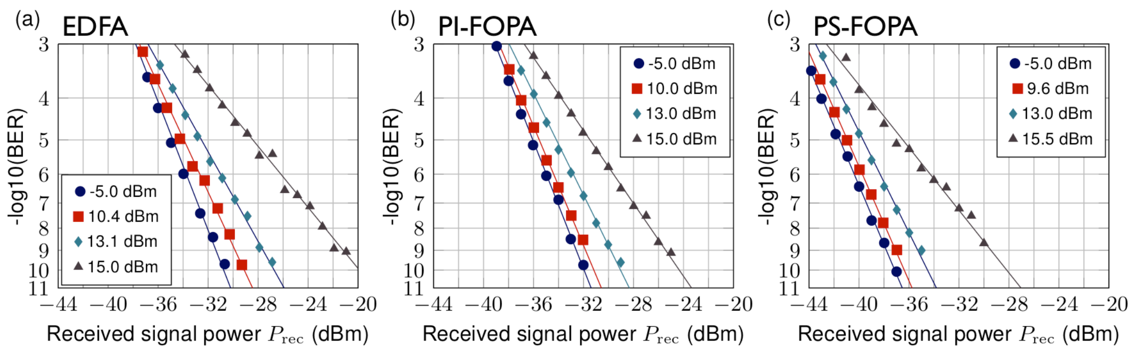

Figure 3. BER versus amplifier received input power for a) EDFA, b) PI-FOPA and c) PS-FOPA based links. Legends indicate signal launch power.

The effect of each of the pre-amplifiers on signals with varying levels of nonlinear distortion is then characterized. The amplifier received input power is varied by an attenuator placed after the fiber link and BER measured (Fig. 3). In the PS case received power is measured as the power in the signal wave only (c.f. Refs. [2,4]). In both the EDFA- and FOPA-based systems, sensitivity is degraded with increasing signal power launched into the link. By comparing BER curves from each of these different systems, the PS system shows greater sensitivity regardless of the signal power at link input.

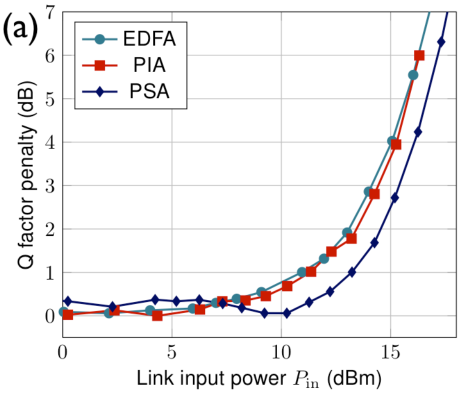

Figure 4. Q-factor penalty vs. signal launch power. Legend indicates pre-amplifier type.

In order to compare the tolerance of these systems to nonlinear distortion in transmission, the input power to each of the pre-amplifiers is set so that at low launch powers the measured BER is low (~10^{-8}, Q~15dB). BER is then measured as a function of signal launch power, with amplifier received power kept constant. Fig. 4 shows the changing Q-factor penalty, extracted from the measured BER. As launch power is increased, the system penalty grows in a similar manner for each system regardless of the amplification scheme used. This indicates that the PSA system is not degraded more than PI systems by intra-channel channel nonlinear distortion (i.e. SPM).

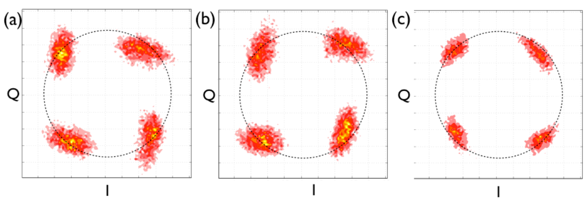

Figure 5. Constellation diagrams at receiver input for +16dBm launch power. a) EDFA, b) PI-FOPA, c) PS-FOPA (dashed circles are a guide for the eye)

To further examine the effect on nonlinear distortion on the operation of the PSA, we compare the output constellation diagrams from EDFA, PI-FOPA and PS-FOPA. Fig. 5 shows that the distortion seen in Fig. 2(c) is un-effected in both of the PI amplifiers, but modified after passing through the PS amplifier. As the output of the PSA is a coherent sum of the signal and conjugate idler, the distribution of the phase noise becomes more symmetric. By inspection, the net effect on error-vector-magnitude, and hence BER, seems minimal. Regenerators based on PSA require the amplifier to operate in the saturated regime, and so here no regenerative effect was expected in the PSA system.

Here the copier-PSA system has been characterized in the presence of intra-channel nonlinear effects on waves widely spaced in wavelength. In a wavelength-division multiplexed system inter-channel nonlinear mixing is likely to be important, its effect on this system remains to be studied. The pump recovery system has a lower bound on input pump power necessary for high fidelity pump replication, providing an additional limit to span length between FOPAs in a copier-PSA link. Preliminary measurements indicate that pump launch powers of up to 20dBm impart no significant penalty in our system, significantly higher power than the limit for the signal.

Conclusions

We have investigated a phase-sensitive amplified link operating in the nonlinear transmission regime. SPM of a 10Gbd DQPSK signal was shown to have a similar effect on sensitivity of systems using an EDFA, PI-FOPA or PS-FOPA. Constellation diagrams show that the PSA modifies the distribution of the nonlinear phase noise on the signal, but with little net effect on BER. These results indicate that the link sensitivity advantage of a PSA based system may be maintained even when operating in the nonlinear transmission regime.

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