DPSK Signal Regeneration with a Dual-Pump Non-Degenerate Phase-Sensitive Amplifier

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Abstract— **We demonstrate, for the first time to our knowledge, regeneration of a 42.66 Gbit/s differential phase shift keyed signal using a dual-pump non-degenerate four wave mixing-based fiber optic parametric amplifier. The regenerative performance of the subsystem is characterized in terms of bit-error-rate against narrow-band and wide-band introduced noise. Whilst a strong receiver sensitivity improvement, up to 20 dB, is noticed against narrow-band noise, against quasi-random (wide-band) noise we observe a regeneration of 2.7 dB.**

Index Terms— **differential phase shift keying (DPSK), optical parametric amplification, phase-sensitive amplification (PSA)**

I. INTRODUCTION

ALL-OPTICAL regenerators are expected to extend the transparent length of high-speed transmission systems and simultaneously lower the energy consumption, compared to their opto-electro-optical counterparts [1]. The emergence of differential phase shift keying (DPSK) as a widely adopted modulation format for long haul transmission has prompted great interest in regeneration schemes for phase encoded signal formats. Such regenerators should provide suppression of the accumulated noise in both the amplitude and the phase of the propagated signal.

Phase sensitive amplification (PSA) has proved its potential for phase noise suppression on DPSK signals. Initial schemes were based on single pump degenerate four wave mixing (FWM) in a fiber [2], [3]. Regeneration based on dual pump degenerate fiber optic parametric amplifier (FOPA) has also been proved both theoretically [4] and experimentally [5]. Using the phase locking scheme proposed in [6] to generate a pair of synchronized and frequency symmetric pump signals, the first practical "black-box" regenerator has been demonstrated in [7]. The regenerative properties of those schemes have been assessed by applying a periodic (single tone) degradation to their inputs.

PSA is also feasible with a dual pump non-degenerate FOPA scheme [8]. This is particularly attractive for wavelength division multiplexing (WDM) applications because it can provide broadband amplification and polarization independent performance and has lower pump power consumption than single pump FOPA [9]. However, although the amplification properties of the dual-pump non-degenerate scheme have been extensively studied [10], its regenerative properties have not been explored.

In this letter, we describe the regeneration of 42.66 Gbit/s DPSK signals using a non-degenerate dual-pump FWM based phase-sensitive FOPA. The idler for the PSA and the pilot tones for pump phase-locking were derived from a frequency comb. We have assessed, for the first time to the best of our knowledge, the performance of a non-degenerate DPSK regenerator in terms of receiver sensitivities under different phase noise conditions. Complete regeneration of periodic distortion (narrow bandwidth noise) was achieved and up to 2.7 dB regeneration of quasi random phase noise (bandwidth exceeding the signal bandwidth) was observed.

II. EXPERIMENTAL DETAILS

The experimental setup is illustrated in Fig. 1. We generated a phase coherent multi-tone signal using a comb generator based on two Mach-Zehnder modulators (~10 dB insertion loss) driven by a 42.66 GHz sine wave. The comb flatness was maintained by a feedback loop, which monitored the spectrum with a Fabry-Perot filter and adjusted the modulators' bias. A tap from the comb signal was used to generate two pilot carriers spaced by 426.6 GHz, whilst the remaining signal was filtered to obtain a signal-idler pair (two subcarriers spaced by 85.32 GHz). The latter were data encoded to produce two 42.66 Gbit/s DPSK WDM channels, carrying a pseudo random binary sequence (PRBS) with a $2^{31} - 1$ pattern length. Phase noise was added by driving a phase modulator with a 56 Gbit/s pattern generator operated from an independent clock. We added two different kind of phase noise: 1) a periodic degradation, by programming the pattern generator with a "1100" pattern giving a 14 GHz square wave distorting signal; 2) a quasi-random distortion, in this case a 56 Gbit/s $2^{15} - 1$ PRBS pattern was selected. In the latter case, the resultant phase noise spectrum exceeded the optical bandwidth of the receiver, and consequently it could be
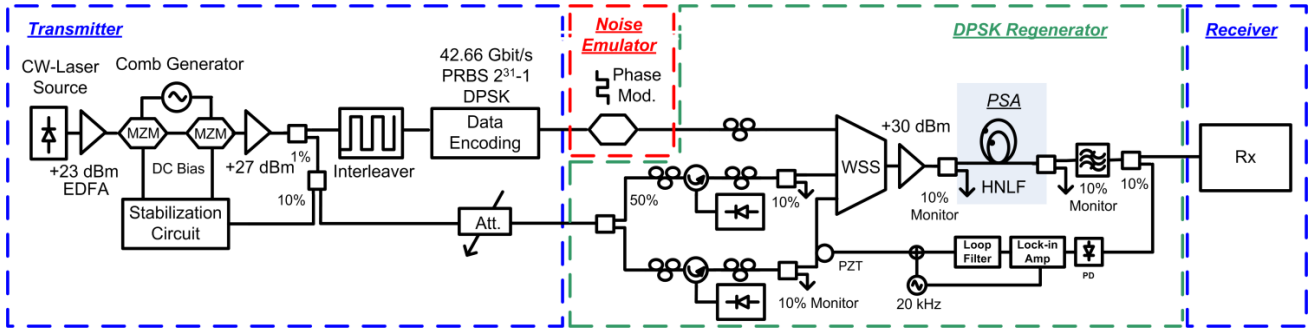
Fig. 1. Experimental setup of the DPSK regenerator.

considered as a quasi-random phase degradation. The optical signal-to-noise ratio at the input of the PSA, (total signal and idler power divided by noise power in 0.1nm) was 44 dB.

At the DPSK regenerator input, the pilot carriers with powers of ~ –17 dBm were used to phase and frequency synchronize two discrete-mode laser [6] based CW pumps by injection locking. This process locally regenerates the seeds by removing their amplitude noise and by amplifying them. The pumps were then combined with the signal and idler using a commercially available continuous band wavelength selective switch (WSS). The combined signals were then amplified to a total power of 30 dBm (the two pumps contributed 93% of the total power) at the input of PSA and launched into a 210 m length of highly-nonlinear fiber (HNLF), which had 14 dB/km attenuation, 0.09 ps/√km polarization mode dispersion coefficient, –0.20 ps/(nm·km) chromatic dispersion and a nonlinear coefficient of 7.4 (W·km)$^{-1}$ (all parameters @ 1550 nm). The HNLF had an increased threshold for stimulated Brillouin scattering (SBS) of 0.8 W, thanks to an Al-doped core [11] and applied strain. A traditional phase locked loop maximized the total output power by controlling a piezoelectric-based fiber stretcher (PZT) in one of the pump paths to compensate for any slow phase drift between the interacting waves arising from acoustic or thermal effects.

The performance of the phase distorted input and the regenerated signals were assessed using a pre-amplified receiver which employed an 85 GHz free spectral range (FSR) asymmetric Mach-Zehnder interferometer (AMZI) and a 0.64 nm filter. A further 42.6 GHz FSR AMZI was used to demodulate the DPSK signal prior to single ended detection (constructive port) and bit-error rate (BER) measurements.

III. RESULTS AND DISCUSSIONS

Fig. 2 illustrates the measured spectra at the output of the PSA regenerator with and without degradation induced by the periodic "1100" pattern. A gain contrast in excess of 12 dB was achieved for both channels simultaneously (signal and idler are equivalent or could be equivalently swapped) in absence of degradation, which was reduced when the signal was degraded by phase modulation.

The regenerative properties of the non-degenerate phase-sensitive FOPA in the presence of periodic degradation are shown in Fig. 3 (a), where the BER is plotted against total received power (both channels). The regenerated BER at the

output of PSA (blue) fell 1 dB from the BER at PSA input without degradation (black) when an input degradation of ±40deg was introduced (red BER curves). The PSA clearly improved the BER performance and restored the eye diagrams of the degraded signals after differential detection (Fig. 3 (b)).
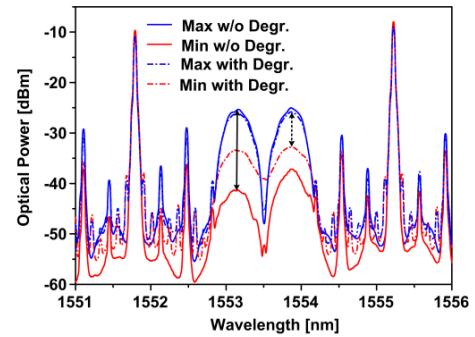

Fig. 2. Measured output spectra of PSA for non-degraded (solid line) and degraded (dashed) signals at minimum (red) and maximum (blue) gain.
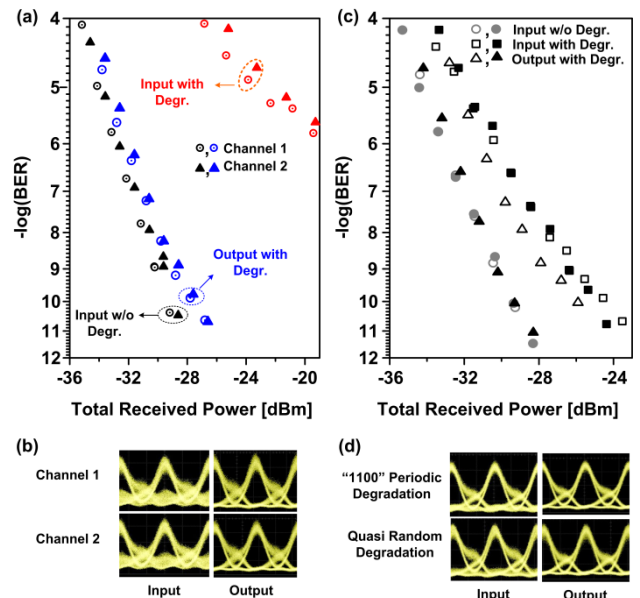

Fig. 3. (a) Measured BER characteristics and (b) eye diagrams at the input and output of the PSA regenerator in the presence of ±40deg of periodic degradation for both channels. (c-d) Comparison of regeneration for equal initial penalties from periodic (filled symbols) and quasi-random (hollow) degradation at the regenerator input (squares) and output (triangles).

Fig. 3 (c-d) compares the performance for levels of periodic and quasi-random distortion that both give a receiver
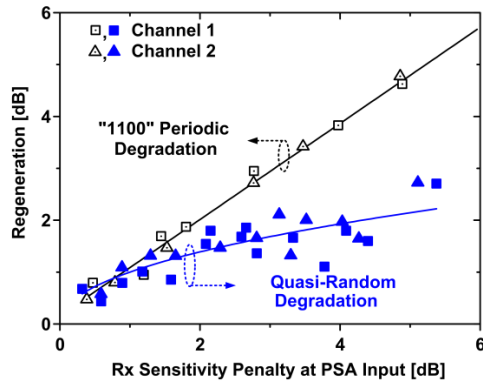
Fig. 4. Non-degenerate PSA regeneration as a function of receiver sensitivity penalty at the input of the PSA for periodic (open symbols) and quasi-random degradation (filled) for channel 1 (squares) and 2 (triangles). Solid lines are shown to guide the eye.

sensitivity penalty of ~4.3 dB at the input of the PSA. Whereas we observed almost ideal regeneration in the case of periodic degradation, in the case of quasi-random degradation the level of regeneration was restricted to 1.6 dB.

The saturation of the improvement with a quasi random degradation is further illustrated in Fig. 4, where the receiver sensitivity penalty at the input of PSA was varied between 0 and 5 dB for both types of degradation. Fig. 4 shows that the regeneration (defined as the difference between the receiver sensitivity at the output of PSA and the receiver sensitivity at the input) followed a linear behavior for the periodic degradation. For this kind of degradation, the performance of the regenerated signal was within 1 dB of the non-degraded back-to-back signal, even for periodic degradations leading to receiver sensitivity penalties of 20 dB (Fig. 3 (a)). On the other hand, for a quasi random degradation, the regeneration tended to saturate as the degradation increased, with a maximum of 2.7 dB. Beyond the range illustrated in Fig. 3, for a quasi random degradation an error floor developed in the regenerated signal. We believe that this is because, in the presence of random phase noise, it is impossible for an optical regenerator to improve the BER of a signal beyond the limit obtained by using an ideal receiver. In this case we believe that the physical mechanism behind the limitation is the conversion of phase noise to amplitude noise. This effect is qualitatively illustrated with the constellation diagrams in Fig. 5. This figure schematically represents the degraded input signal (in both cases the added phase noise had the same standard deviation) and the corresponding output signal. For a periodic signal, whilst the gain is somewhat reduced by the phase modulation (see also Fig. 2), no significant additional amplitude noise is induced. However, for quasi-random degradation a conversion of phase noise to amplitude noise is clearly apparent, leading to a reduction in the overall signal quality. This enhanced amplitude noise at the PSA output signal for a quasi-random degradation is in stark contrast to the simple gain reduction observed for a periodic degradation. We also believe that this amplitude noise could be reduced by operating the PSA in a saturated mode, or by cascading the PSA with a phase preserving amplitude regenerator, although any associated error floors due to initial phase errors of more

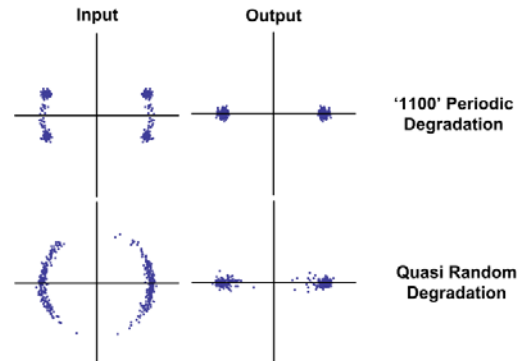than 90 degrees would inevitably be locked in.

Fig. 5. Analytical prediction of normalized PSA input and output at 14dB on-off gain for both degradations.

IV. CONCLUSION

We report, for the first time, the regeneration in terms of receiver sensitivity of a 42.66 Gbit/s DPSK signal by a dual pump non-degenerate PSA. We have demonstrated that the phase transfer characteristic of the PSA provides up to 2.7 dB regeneration of a signal degraded by quasi random phase noise, and have identified phase to amplitude conversion as the limiting factor for regeneration performance.

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