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Demonstration of phase-regeneration of DPSK signals based on phase-sensitive amplification

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Abstract: Amplification and simultaneous phase regeneration of DPSK signals is demonstrated using a phase-sensitive amplifier. Phase-sensitive gain is achieved in a Sagnac fiber interferometer comprised of non-polarization maintaining, highly nonlinear fiber operating in the un-depleted pump regime. Both the pump and signal are RZ-DPSK pulse trains. The amplifier is capable of producing greater than 13 dB of phase-sensitive gain for an average pumping power of 100 mW, and easily reduces the BER of the regenerated DPSK signal by two orders of magnitude compared to the un-regenerated signal, corresponding to a negative power penalty of 2 dB. Careful optimization of the regenerator reveals much stronger BER improvement.

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1. Introduction

Differential phase-shift keying (DPSK) has become the format of choice for long-haul optical transmission systems, due to the 3-dB improvement in receiver sensitivity compared to on-off keying (OOK) and enhanced tolerance to dispersion and nonlinear effects, particularly intra-channel four-wave mixing (FWM). DPSK systems with balanced detection can tolerate a large amount of amplitude noise compared to OOK since, in DPSK systems, errors occur only when pulse-to-pulse phase relationships deviate by more than $\pi/2$ from their original values, regardless of the amplitude at detection. Excluding timing jitter, the primary limitation of a DPSK transmission system is the accumulation of linear and nonlinear phase noise. Linear phase noise results from imperfections in optical modulators and from amplified spontaneous emission (ASE) in optical amplifiers. Nonlinear phase noise results from intra- and inter-channel nonlinearities such as self phase modulation (SPM) and cross phase modulation (XPM) that convert amplitude noise to phase noise, which is known as the Gordon-Mollenauer effect. As a result, amplitude noise from modulators, ASE, dispersion-induced pattern effects and nonlinearities such as inter-channel FWM all introduce nonlinear phase noise that limits system performance. Experiments have shown that when the nonlinear contribution to phase noise becomes dominant the 3-dB improvement in receiver sensitivity for balanced DPSK detection can be lost [1], negating a major advantage of using DPSK over OOK. Several techniques have been proposed for managing fiber nonlinearity [2, 3] to reduce the accumulation of nonlinear phase noise, including mid-link spectral inversion [4], however these management schemes will not remove phase noise once it accumulates. Post-transmission nonlinear phase shift compensation (NLPSC) can effectively mitigate SPM-induced nonlinear phase noise [5, 6] but cannot correct for linear phase noise or the effects of inter-channel XPM.

To accomplish DPSK regeneration it is necessary to equalize the pulse relative amplitudes while simultaneously restoring the encoded differential phase shifts. So far, the topic of DPSK regeneration has been divided between schemes that address amplitude and phase regeneration independently, since several traditional amplitude regeneration techniques inherently degrade phase information. Phase-preserving DPSK amplitude regeneration has been proposed based on XPM combined with optical filtering [7], and using a modified nonlinear optical loop mirror (NOLM) [8], but has yet to be demonstrated experimentally. Numerical analysis has shown that FWM-based amplitude regenerators are favorable for DPSK systems, since phase information can be preserved [9]. Phase-regenerative amplification of a DPSK signal suffering only phase noise has been demonstrated in a combined Sagnac-SOA structure [10] for an input Q-factor $> 14$ dB.

The phase-sensitive amplifier (PSA) has emerged as an interesting candidate for optical amplification of both on-off keyed and DPSK signals. PSA’s have been widely realized in nonlinear optical loop mirrors (NOLM) for amplification of high speed signals [11]. They offer the potential of providing signal gain with a noise figure less than the 3-dB limit of
phase-insensitive amplifiers [12] and also may act as limiting amplifiers [13]. PSA’s also show regenerative characteristics when they are used to store solitons pulses in optical buffers [14]. Recently we proposed using a PSA for simultaneously regenerating both the amplitude and phase of a DPSK signal [15], with the potential for restoring differential phase shifts to almost exactly 0 or π even for large values of input phase noise while restoring pulse amplitudes for > 3-dB input amplitude noise. Two regimes of operation for the PSA-based DPSK regenerator were discussed: an un-depleted pump PSA, which performs nearly ideal phase-only regeneration, and a depleted-pump PSA that would combine phase and amplitude regeneration. Here, we present, for the first time, experimental results for an un-depleted pump PSA performing phase regeneration of a phase-noise degraded DPSK signal.

2. Experimental setup

The experimental setup for the PSA-based DPSK regenerator is shown in Fig. 1. An RZ-DPSK signal is generated using a 10 Gb/s pulse pattern generator, a phase modulator and a Mach-Zehnder modulator (MZM) operating as a pulse carver. The clock signal drives the MZM to generate a 50% duty cycle RZ pulse train at 10 Gb/s. Phase information is then impressed onto the pulses using the phase modulator, resulting in a PRBS data stream of length 231-1. A 90/10 splitter is used to separate a pump (for the PSA) and signal (to be regenerated). The pump arm contains an optical isolator, fiber stretcher and free-space delay line, which allows temporal alignment of pump and signal pulses at the input to the PSA. The signal arm comprises a variable optical attenuator, phase modulator and optical circulator, as well as polarization controllers. The optical attenuator allows adjustment of the ratio of pump to signal power at the input to the PSA. Due to non-uniform losses in the pump/signal paths, the minimum ratio in this configuration is about 13 dB. Phase noise is added to the signal by driving a phase modulator at high frequencies (> 6 GHz) using an RF synthesizer. Using this method we ensure sufficiently large phase deviations are generated between adjacent bits in the 10 Gb/s DPSK pulse train, so that differential phase shifts vary significantly from their original 0 or π values. The length mismatch between the pump and signal paths (prior to the PSA input) is slightly greater than 3 meters, so that the two pulse trains are de-correlated by at least 150 bits.

The PSA is comprised of a 3-dB coupler and 6058 meters of highly nonlinear fiber (HNLF), with a total insertion loss of about 5 dB and an effective nonlinear coefficient of 9.75 W⁻¹km⁻¹. The pump and signal polarizations are aligned external to the PSA. An intra-loop polarization controller ensures maximum reflection of the pump and signal to their respective output ports, and the reflected pump is blocked by an optical isolator. The regeneratively amplified signal is extracted from the optical circulator. A fraction of the regenerated signal is sent to the slow photo-detector to monitor the output average power. The photo-detector output combined with a feedback circuit and the fiber stretcher form a phase-locked loop that is used to stabilize the phase relationship between pump and signal against environmental fluctuations. For maximum gain and best regeneration performance, the input phase difference should be locked to a value slightly less than π/2 when the PSA operates in the un-depleted pump regime. The remaining signal light is divided between a sampling oscilloscope and the error detector.
3. Results

The principle of operation for PSA-based phase regeneration has been outlined in [15]. Essentially, the counter-propagating fields, corresponding to constructive and destructive interference between the pump and signal respectively, undergo different amounts of nonlinear phase shift leading to an imbalance in the interferometer. As a result pump light can be transferred to the signal output port, leading to phase-sensitive gain. The phase-sensitive nonlinear phase shift difference between the two counter-propagating waves proportional to

$$\gamma \cdot L_{\text{eff}} \cdot \sqrt{P_p(0) \cdot P_s(0)} \cdot \sin(\delta) \approx \varphi_p \cdot \sin(\delta)$$

determines the signal gain, where $\gamma$ is the effective fiber nonlinear coefficient, $L_{\text{eff}}$ is the effective length, $P_p(0)$ and $P_s(0)$ are the input pump and signal peak powers and $\delta$ is the input phase difference. In the approximation of large nonlinear phase shift $|\varphi_p| = \pi / 2$ and the maximum signal gain occurs when the input phase difference $\delta = \pm \pi / 2$. For those conditions the output signal phase can be calculated directly as $\varphi_{\text{out}} = \varphi_o + \varphi_p \cdot \sin(\delta) + \varphi_{\text{am}}$, where $\varphi_o$ is a term proportional to the input pump and signal powers, amplifier nonlinear coefficient and length. From this equation it is clear that input signal phase shifts of near $\pi$ are mapped to corresponding output phase shifts of $\pi$ through a sign change of the second term. On the other hand, we note that changing the phase of the pump between values of 0 and $\pi$ (for a constant signal phase) does not affect the value of output signal phase. This characteristic is exploited in the experiment as a convenient and practical means of reducing stimulated Brillouin scattering (SBS) in the HNLF, which can significantly degrade regeneration results, by using a pump with two pseudo random phase states of 0 and $\pi$. The SBS threshold with pseudo-random phase modulation was greater than 23 dBm of pump average power, compared to only ~5 dBm when a purely amplitude-modulated pump was used, and the resulting contribution to output amplitude noise on the regenerated signal arising from SBS is minimal.
Phase regeneration is verified by comparing the Q-factor of the demodulated eye and BER measurements for the degraded versus regenerated signals after interferometric demodulation and balanced detection. The frequency of the RF signal used to drive the signal phase modulator is non-commensurate with the signal bit rate to simulate random phase noise. The amplitude of the RF signal is chosen so that adjacent bits in the DPSK data stream acquire phase errors of up to 40 degrees. Figure 2(a) shows the electrical eye diagram for the demodulated DPSK signal without phase degradation, for an input optical power to the demodulator of -9 dBm. The eye is widely open, with a Q-factor of the demodulated eye of about 8.7. Without the addition of phase noise the signal is error free even for very small values of received optical power. Figure 2(b) shows the eye diagram with the addition of phase noise at a randomly chosen frequency > 6 GHz, for the same received power of -9 dBm. The Q-factor of the demodulated eye is severely degraded and is estimated to be slightly greater than 3, with all degradation resulting from the addition of phase noise. Figure 3 shows BER results for the degraded signal. For the received power of -9 dBm this signal gives a BER of $\sim 1.5 \times 10^{-6}$.

The degraded signal was regenerated using a pump average power of 100 mW, corresponding to 200 mW peak power, and a ratio of launched pump power to signal power of 13 dB. The phase sensitive nonlinear phase shift difference is about $\pi/4$. For these measurements smaller power ratios generally give better regeneration performance, in agreement with our theoretical calculations. The attenuated pump power transmitted through the PSA, in absence of the signal, is slightly greater than 32 mW. A small fraction of this ($\sim 1$ percent) is detected as leakage through the signal output port, resulting from imperfections in the 3-dB coupler and polarization rotation within the loop. Without the pump, the transmitted signal at the circulator output is 660 $\mu$W. When both the pump and signal were present the maximum output power obtained for these measurements was 8.6 mW, corresponding to 11.4 dB of phase-sensitive gain after accounting for pump leakage. Maximum pump depletion is less than 30 percent which agrees with our calculations corresponding to a phase-sensitive nonlinear phase shift difference of about $\pi/4$.

Figure 2(c) shows the regenerated signal after demodulation and balanced detection, for a received power of -9 dBm. Clear improvement of the eye diagram is obtained, with only small residual noise. The regenerated Q-factor of the demodulated eye in this case is 9.4, greater than the SNR obtained for the degraded signal. Most of the residual noise that appears results from amplitude noise, with the phase noise being almost completely cleaned. Figure 3 compares the BER for degraded and regenerated signals. On average, the BER improvement is slightly over two orders of magnitude after regeneration, and a negative power penalty of 2 dB is achieved. It is worth noting that, in the low BER regime, measurements are limited by the stability of phase-locking at the input to the PSA and by slow variations between the pump and signal polarizations, which are not inside polarization-maintaining fiber in this experiment. These factors affect results over the entire range of measurements, however at
higher BER (lower received power) the measurement time is shorter. BER reductions of greater than 4 orders of magnitude are easily obtained by carefully aligning the polarizations at the input, demonstrating even further potential advantages of a PSA-based DPSK regenerator.

4. Conclusions

We have demonstrated phase regeneration of a phase-noise degraded DPSK signal using a PSA operating in the un-depleted pump regime. The SNR of the degraded signal is improved from 3 to 9.4 after balanced detection, and the corresponding BER improvement is slightly greater than two orders of magnitude. The PSA provides 11.4 dB of optical gain compared to the case of signal transmission through the PSA without the pump present. The regenerated SNR is limited by output amplitude noise rather than phase noise, which arises from the conversion of phase-to-amplitude noise in an un-depleted pump PSA. When the PSA gain is sufficiently large this noise contribution is strongly suppressed, making un-depleted pump PSA’s useful for inline processing of DPSK signals. Additionally, the extension of current results to incorporate amplitude regeneration is straight-forward. While we note that practical PSA-based regenerators require an independent pump source frequency locked to the incoming DPSK signal, methods for providing frequency and phase locking for carrier-suppressed modulation formats such as DPSK are already available [16].