Research in parametric optical amplification and injection locking focused on high bit rate optical communication systems applications

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Abstract. In this dissertation, the properties of the all-optical processes of phase sensitive parametric amplification and injection locking, are thoroughly investigated, through numerical simulations and experiments, in order to design integrated optical devices that can improve the performance of coherenct optical communications. Exploiting the phase noise suppression that the phase sensitive parametric amplifier can provide, a novel 40 Gb/s RZ-DPSK regenerator based on the single pump topology is proposed, which adops a realistic solution for the all-optical generation of an idler wave identical to the signal, dealing with the unresolved problem of the practical implementation of the specific devices. Taking into consideration the amplitude noise suppression and the phase replication properties of the injection locked semiconductor laser, we propose the use of the specific device as an alternative solution for (D)PSK and (D)QPSK signal regeneration. From the above properties, the injection locked semiconductor laser is also proposed as an additional unit in a DPSK/ASK receiver in order to provide better discrimination of the two different data streams and improve the performance of the specific modulation format.

Keywords: Parametric amplification, injection locking, coherent communication systems, all-optical regeneration, orthogonal modulation formats.

1 Dissertation Summary

Coherent optical communication systems that rely on phase modulation formats such as differential phase-shift keying (DPSK), quadrature phase-shift keying (QPSK) etc., currently emerge as an alternative to on–off keying (OOK) for long-haul transmission. The superiority of the coherent systems is based on three fundamental advantages: The first one originates from the balanced detection of the phase modulated signals which offers a 3-dB improvement in receiver sensitivity over direct detection of OOK. The second one is their enhanced tolerance to fiber nonlinearities and basically to interchannel cross-phase modulation (XPM). And the third one is the plethora of the advanced multi-level phase modulation formats providing enhanced bandwidth efficiency. Nonetheless, nonlinear phase noise is the major limitation for

*Dissertation Advisor: Dimitrios Syvridis, Professor the performance of these systems requiring the periodic regeneration of the signal for long-haul transmissions. The potential for commercial deployment of phase modulation formats has triggered worldwide the research activity on the optical manipulation of signals modulated in phase.

The all-optical regeneration of phase modulated signals is carried out by periodic suppression of the amplitude noise, which limits the build up of the non-linear phase noise, or by direct phase noise suppression.

In this dissertation we thoroughly investigate the processes of phase sensitive parametric amplification, which offers direct phase noise suppression, and injection locking, which offers amplitude noise suppression and phase replication of the injected signal.

In the paragraphs below we present the regenerator architectures that have been emerged from the current investigation and provide performance improvement of coherent optical communication systems.

2 Phase sensitive amplification

The FWM is a non-linear process that takes place inside non-linear media such as optical fibers or semiconductor devices (e.g. lasers, optical amplifiers) and depends on the third order susceptability of the medium. In this process, two propagating waves (ω_1, ω_2), inside the medium, create a perturbation to the optical power dependent refractive index which then modulates the phase of each wave with a characteristic frequency that equals to the beating frequency of the two waves, $\omega_{mod}=\omega_2-\omega_1$. As a result, each wave develops side-bands with spectral distance from the central frequency equal to ω_{mod}, which essentially leads to the generation of two new waves ($\omega_3=\omega_1-\omega_{mod}$, $\omega_4=\omega_2+\omega_{mod}$).

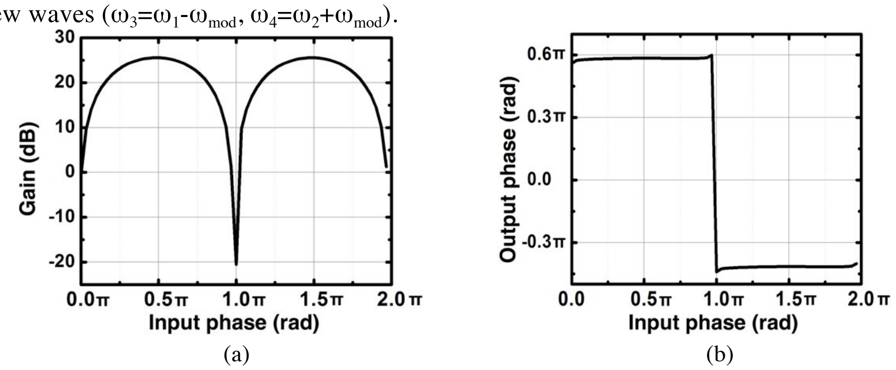


Fig. 1. Gain (a) and phase response (b) of a PSA as a function of the input signal's phase.

If four waves with the above spectral distances are being launched at the input of the non-linear medium, then depending on the total phase difference ($\Delta\phi$) between the four waves, energy can be trasnferred from frequencies ω_1 and ω_2 to ω_3 and ω_4, if $\Delta\phi=\pi/2$ (parametric amplification), or vice versa, if $\Delta\phi=-\pi/2$ (parametric absorption).

The parametric amplifiers are based on two main topologies, single and dual pump, depending on the number of strong waves that are used in order to amplify the weak waves. The weak waves are called signal and idler. The presence or the absence of the idler wave at the input of the parametric amplifier determines the phase sensitive or phase insensitive gain of the amplifier, respectively.

Phase sensitive amplification exhibits a very interesting property. If the phase characteristics of the idler and signal waves are identical, then the gain curve of the amplifier as a function of signal's phase presents periodicity equal to π, while the phase response of the signal at the output of the amplifier is a step function with periodicity and step both equal to π. These properties make PSA the ideal device for all-optical regeneration of phase modulated signals.

2.1 Regenerative performance of a single pump PSA

In order to evaluate the noise suppression characteristics of the PSA, we investigate, through numerical analysis, its behavior to sinusoidal perturbations of the intensity and phase of the input signal. Depending on the power of the input signal, the PSA operates in two different regimes. For low input powers, PSA operates in linear regime in which the amplifier exhibits strong phase noise suppression (≈ 18 dB) and high phase noise to amplitude conversion (≈ 26 dB) . For higher input powers, PSA operates in non-linear regime in which the phase noise suppression is degraded (≈ 12 dB) but strong amplitude noise suppression (< 12 dB) is observed while the phase noise to amplitude conversion is strongly suppressed (≈ 20 dB). The behavior of the PSA in these two regimes is depicted in the diagrams of figure 2.

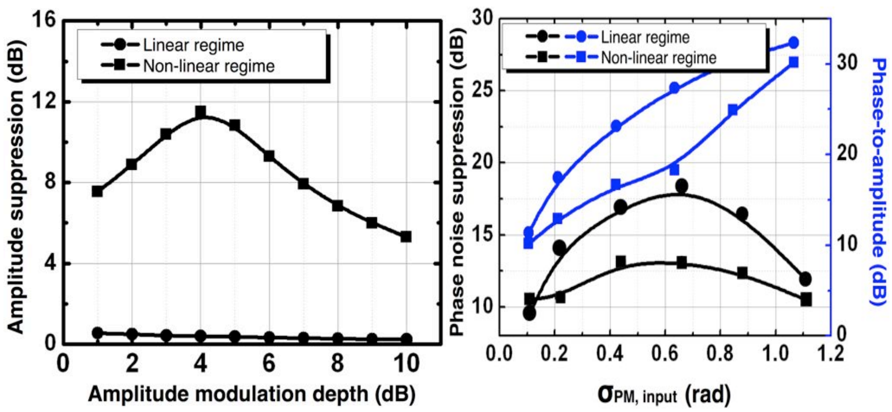


Fig. 2. PSA response to sinusoidal perturbation

Subsequently, we investigate the regenerative capabilities of the single pump PSA using RZ-DPSK signals. In order to evaluate its performance, we compare the quality of the RZ-DPSK signal, which is quantified by the Q factor, at the output of three different long-haul transmission links. The first link is a typical transmission link without the use of any regeneration device, consisting of multiple spans of 80 km of dispersion compensated transmission and amplification of the signal at the end of each span. The second link is based on a popular topology which uses recurrent units of saturated PIAs placed every 480 km along the transmission link. Finally, the third link uses a PSA as a regenerative unit which is placed in an intermediate point of the transmission line.

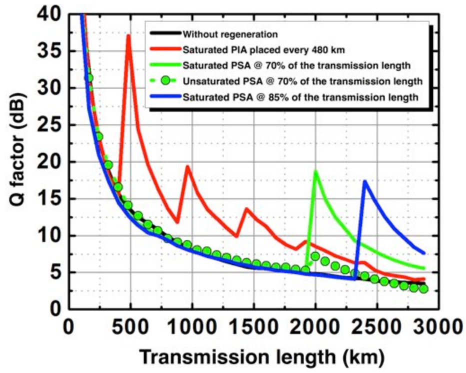


Fig. 3. Performance comparison between three different optical transmission links for a 40 Gb/s RZ-DPSK transmitted signal.

As can be seen in the figure above, the saturated (non-linear regime) PSA exhibits remarkable regenerative performance due to its strong amplitude and phase noise suppression, improving the quality of the signal up to 10 dB higher than the unsaturated PSA and the multiple saturated PIAs.

2.2 RZ-DPSK regenerator based on single pump PSA

As we mentioned before, the idler wave at the input of the amplifier has to be identical to the signal in order to ensure the regenerative capabilities of the PSA. This constitutes the most significant obstacle for the implementation of this device and till now no realistic solution has been proposed, at least for the topology of the single pump PSA. In this dissertation we propose a novel architecture of a RZ-DPSK regenerator based on single pump PSA, in which the all-optical generation of an identical to the signal idler wave is achieved. The topology of the proposed regenerator is depicted in the block diagram of figure 4 and consists of three main units. The first unit undertakes the all-optical generation of two identical and phase locked intensity modulated RZ waves at the wavelengths λ_s and λ_i, using a PIA implemented in a highly non-linear fiber (HNLF). The RZ pulses have the same repetition rate as the received RZ-DPSK signal and λ_s is the same as the received wavelength. The second unit is the most important unit of the regenerator as it undertakes the all-optical and coherent transfer of the phase information of the received signal to the phase of each one of the locally generated RZ waves. Firstly, a delay interferometer (DI) transfers the DPSK information of the received signal to its amplitude.

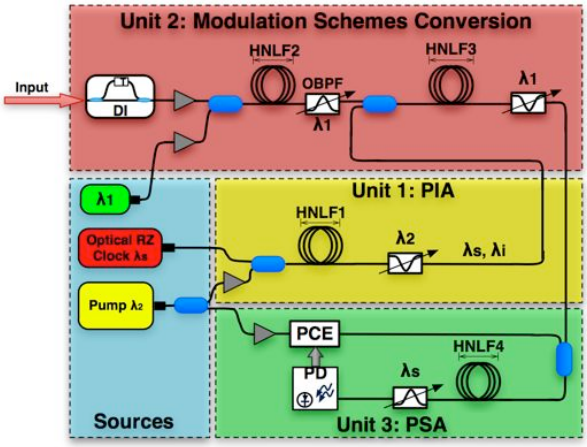
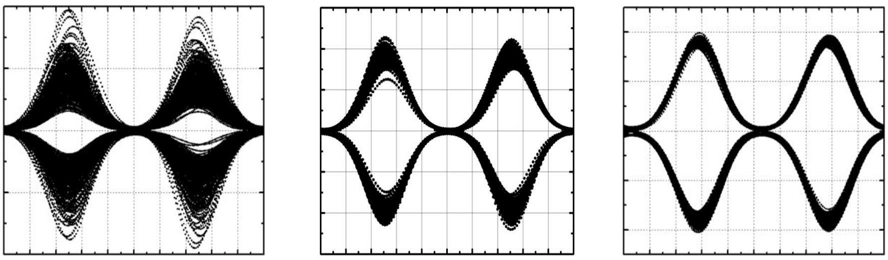


Fig. 4. RZ-DPSK regenerator based on single pump PSA. DI: delay interferometer, OBPF: optical band-pass filter, PCE: phase control element and PD: photodiode.

As a result, at the output of the DI we receive a RZ-OOK signal at the amplitude of which is imprinted the phase information and the total noise (amplitude and phase noise) of the received signal. The RZ-OOK signal is then converted into NRZ-OOK using an all-optical technique that is based on cross-phase modulation (XPM), which takes part in a second HNLF, and the final signal is transferred to the phase of λ_s and λ_i using the XPM process, which takes place in a third HNLF. The two identical RZ-DPSK signals (λ_s, λ_i) at the output of this unit are imported into the third unit in which, through phase sensitive amplification, the regeneration of λ_s is achieved. The quality of the regenerated RZ-DPSK signal for the two different PSA operating regimes can be observed in the eye diagrams of figure 5.



(a) (b) (c)

Fig. 5. 40 Gb/s RZ-DPSK signal before (a) and after regeneration for PSA operating in linear (b) and non-linear (c) regime.

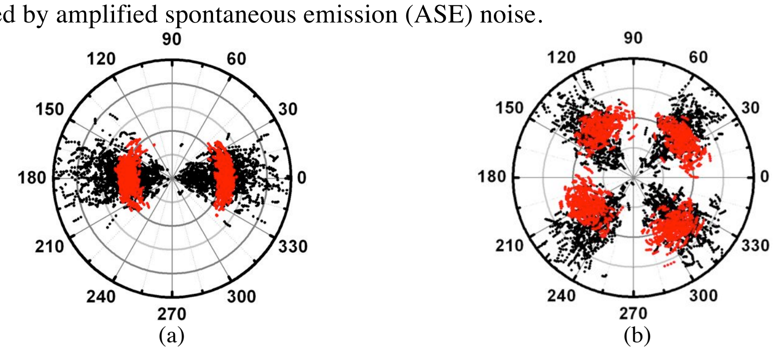
As it was expected from the analysis of the previous paragraph, the proposed regenerator exhibits better performance when the PSA operates in the non-linear regime improving the optical SNR of the received signal up to 28 dB.

3 Injection locking

Injection locking refers to the frequency effects that can occur when a harmonic oscillator (slave) is disturbed by a second oscillator (master) operating at a nearby frequency. When the coupling is strong enough and the frequencies near enough, the master oscillator can capture the slave oscillator, causing it to have essentially identical frequency as the master. This process can occur in a variety of oscillators in which the semiconductor lasers are included. In semiconductor lasers, the strength of the coupling is proportional to the injection ratio, R, which is given by the ratio of the injected power of master laser to the emitted power of the free running slave laser. As injection ratio increases the locking range of slave laser broadens enabling it to follow higher frequency perturbations of the injected signal. Through injection locking, slave laser acquires a variety of characterics such as the ability of replicating the phase information and suppress the amplitude noise of the injected signal, the enhancement of its modulation frequency, the reduction of its relative intensity noise, the suppression of its linewidth and the suppression of its side modes. Taking into consideration the above capabilities of the injection locked laser we propose its use as a cost effective, energy efficient and low complexity regenerator for phase modulated signals.

3.1 Regenerative performance of a single mode semiconductor laser

Using the modified rate equations appeared in [??] we modeled the master-slave system and investigated the phase replication and amplitude noise suppression capabilities of a semiconductor single mode injection locked laser for different phase modulation schemes and bit rates of the injected signal. The injection locked laser exhibits remarkable regenerative performance demonstrating modulation scheme transparency, supporting QPSK signals, high bit rate data replication, supporting up to 25 Gbaud/s, and strong amplitude noise suppression reaching up to 10 dB. In the polar diagrams of figure 6 is depicted the quality improvement that the injection locked laser can provide to a 25 Gb/s PSK and 50 Gb/s QPSK injected signal degraded by amplified spontaneous emission (ASE) noise.



(a) (b)

Fig. 6. Polar diagrams of PSK (a) and QPSK (b) regenerated signals of 25 Gbaud/s. Black points correspond to master laser complex optical field and red points correspond to slave laser complex field.

To verify the performance of the proposed regenerator we realized the experimental set up of figure 7 and investigated the behavior of slave laser for 10 Gb/s DPSK injected signal degraded by two different noise cases; ASE noise and sinusoidal amplitude perturbations.

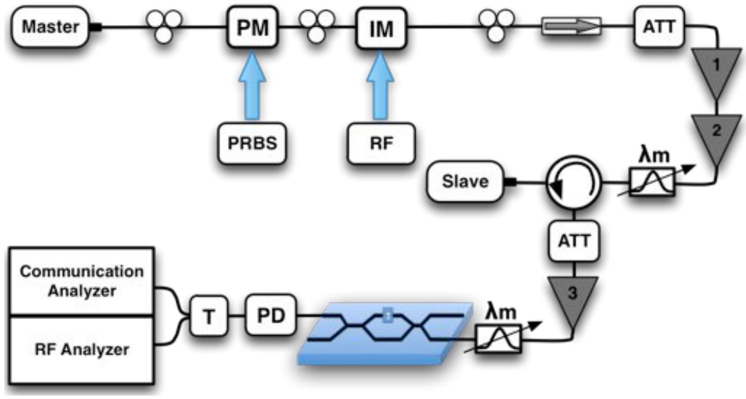


Fig. 7. Experimental set up of the injection locked laser regenerator. PM: phase modulator, IM: intensity modulator, ATT: attenuator, PD: photodiode, PRBS: pheudorandom bit sequence generator, RF: radio-frequency generator.

In figure 8 are depicted the regenerated signals for the two different noise cases and in figure 9 are depicted the corresponding bit error rate (BER) measurements as a function of the received power at the input of the third EDFA.

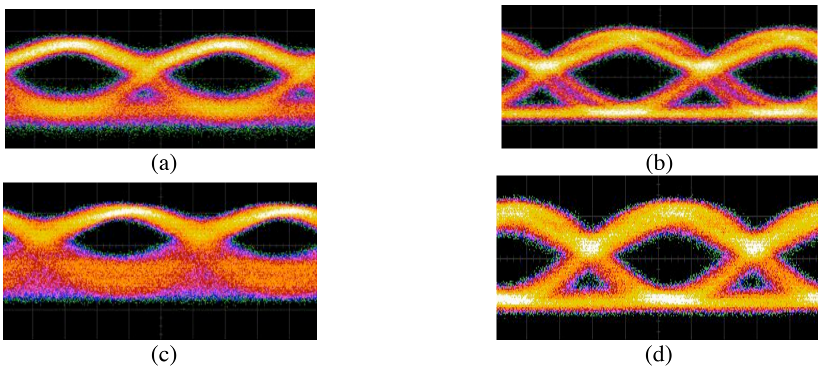
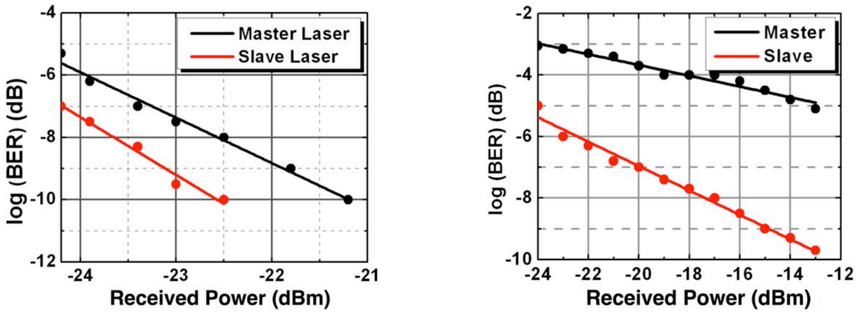


Fig. 8. Eye diagrams of 10 Gb/s DPSK signal before and after regeneration. Figures (a) and (c) correspond to ASE degraded signal and (b) and (d) correspond to amplitude noise degraded signal.



(a) (b)

Fig. 9. (a) BER measurement as a function of the receiver power for ASE degraded signal of OSNR equal to 30 dB. (b) BER measurement as a function of the receiver power for a signal degraded only by strong amplitude perturbation of 1 GHz.

Due to phase to amplitude noise conversion in the case of ASE degraded injected signal, the power penalty that the regenerator provides is limited to 1.5 dB. On the other hand, if the injected signal is degraded only by amplitude noise then the power penalty increases to the remarkable value of 11 dB demonstrating error free data recovery at the receiver.

3.2 Regenerative performance of a Fabry-Perot semiconductor laser

Using the same experimental set up as before (fig. 7), we replaced the single mode semiconductor laser with a Fabry-Perot (FP) laser in order to evaluate its capability of single mode emission, that injection locking can provide to it through side mode suppression, and its regenerative performance. As can be seen in the figures below, the injection locked FP laser demonstrates single mode operation in a bandwidth of 16.4 nm arround its central emission wavelength, with side mode suppression ratio (SMSR) equal to 45 dB, for an injection ratio of -11 dB.

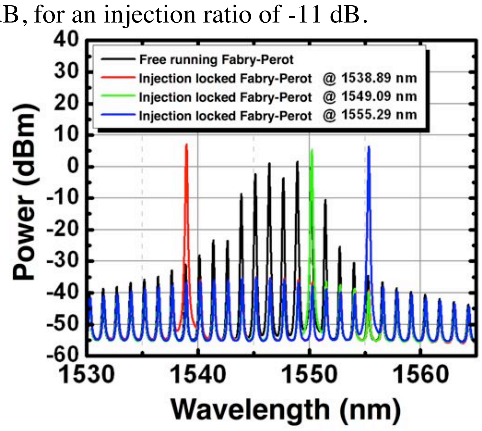


Fig. 10. Single mode operation of the injection locked Fabry-Perot laser for three representative emission modes.

In figure 11, the eye diagrams of the degraded by amplitude noise input and the regenerated output differentially phase shift keying (DPSK) signal are depicted for the above three different wavelengths (1538.89 nm, 1549.09 nm and 1555.29 nm). The figure shows clearly that FP laser is capable of suppressing the unwanted amplitude noise within a wavelength band of 16.4 nm. Outside this region, FP laser is able to lock but the injection level needed for single-mode operation is extremely high to allow limiting amplification and noise suppression.

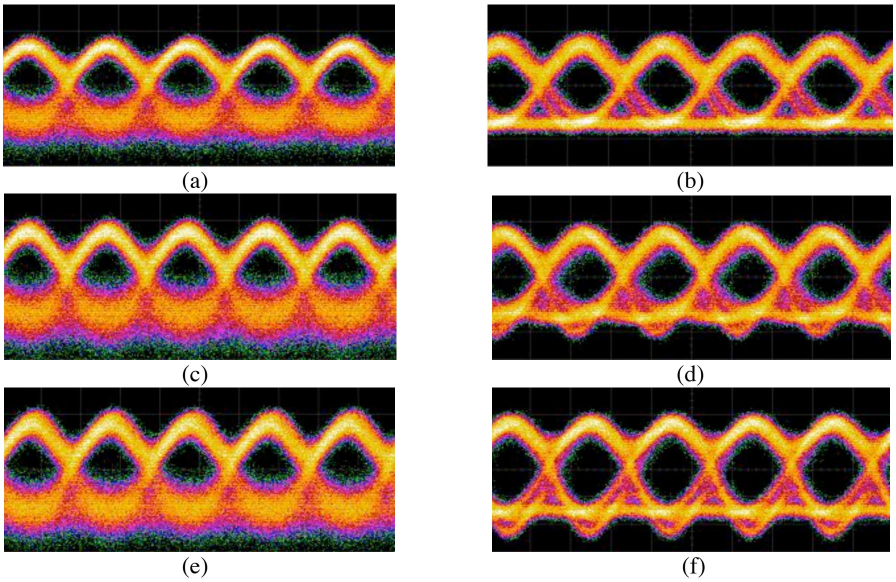


Fig. 11. 10-Gb/s DPSK eye diagrams of the input signal degraded by ASE noise at 1538.89 nm (a), 1549.09 nm (c) and 1555.29 nm (e) and the corresponding regenerated output (b, d, f).

Figure 12 shows a series of BER measurements conducted for input OSNR equal to 23 dB, which further prove the remarkable amplitude limitation properties of the proposed injection locked laser amplifier. The amplitude noise level was adjusted appropriately so as the input signal to exhibit constant BER for every wavelength inside the investigated spectral range. The FP laser provides a reduction of 12 dB in the required receiving power for the achievement of BER performance equal to 10^{-3}.

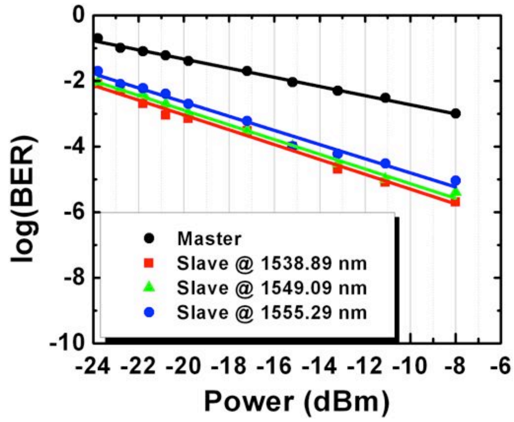


Fig. 12. BER performance as a function of the receiveing power for degraded master signal (black trace) and the corresponding regenerated signal at the output of the slave at 1538.89 nm (red trace), 1549.09 nm (green trace) and 1555.29 nm (blue trace).

3.3 Alternative application of injection locked semiconductor laser

Apart from its regenerative use, the injection locked laser can find a number of alternative applications providing quality improvement and capacity enhancement of future transmissions. In this dissertation, we propose a modified receiver based on the injection locking technique for the performance improvement of the novel orthogonal modulation scheme DPSK/ASK.

DPSK/ASK transmitter relies on the simultaneous modulation of both phase and amplitude of the signal with two different data streams, which doubles the bandwidth efficiency of the signal. Once received, the DPSK/ASK signal is driven through a 3 dB coupler into a direct detection receiver and a DPSK receiver for the demodulation of each data stream. Due to amplitude fluctuations at the DPSK receiver, caused by the remaining ASK information, the initial ASK extinction ratio must be kept at low values (<3dB) in order to ensure high quality of the demodulated DPSK signal. However, if we insert an injection locking unit at the input of DPSK receiver, the unwanted amplitude fluctuations can be suppressed improving DPSK quality and enabling the usage of higher ER of the ASK signal providing total performance improvement of the DPSK/ASK tranceiver. The experimental set up of the proposed modified receiver is depicted in the block diagram of figure 13 and its performance compared to the typical DPSK/ASK receiver is depicted in figure 14.

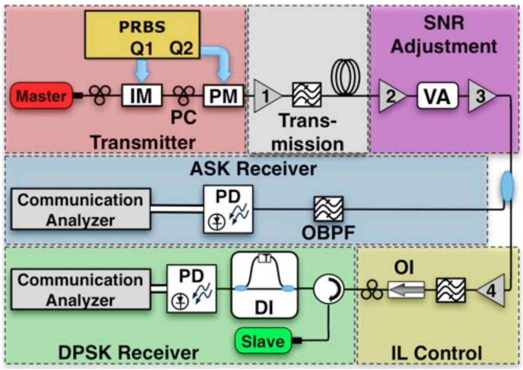


Fig. 13. Block diagram of the experimental setup. PM:phase modulator, IM: intenesity modulator, PRBS: pseudorandom binary sequence, EDFA1: boost amplifier, EDFA2, pre-amplifier, EDFA3: saturated amplifier, EDFA4: injection ratio controller, VA: variable attenuator, PD: photodiode, OBPF: optical band-pass filter, PC: polarization controller, DI: delay interferometer, OI: optical isolator.

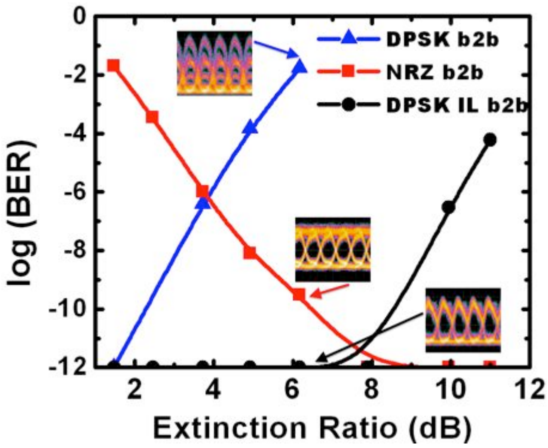


Fig. 14. BER measurements as a function of ER for the 10-Gb/s ASK signal after direct demodulation (red squares) and the 10-Gb/s DPSK signal demodulated with (black circles) and without injection locking (blue triangles).

The proposed receiver allows the usage of ER up to 8 dB maintaining the high quality of the ASK and DPSK data streams for longer transmission lengths. Numerical simulations of the above transeiver demonstrated the error free detection of 10 WDM DPSK/ASK channels for transmissions up to 800 km for 20 Gb/s/channel and up to 400 km for 50 Gb/s/channel.

4 Conclusions

In this dissertation, three novel device architecture for all-optical processing have been proposed providing performance improvement of transmissions based on high efficiency modulation formats.

A RZ-DPSK signal all-optical regenerator based on single pump PSA is for the first time proposed, employing a realistic solution for the all-optical generation of an identical to the received signal idler wave. The specific regenerator can handle RZ-DPSK signals up to 40 Gb/s providing SNR improvement of up to 28 dB. The proposed regenerator can also be implemented using semiconductor optical amplifiers leading to footprint minimization, lower energy consumption and lower complexity.

The injection locked laser is for the first time proposed as an alternative all-optical regenerator for phase modulated signals. The specific regenerator can be placed along the optical path or at the input of the receiver improving the quality of the signal and reducing the required power for a given BER. It can also be placed at the output of a PSA operating in the linear regime suppressing the amplitude noise generated by the specific amplifier and leading to total noise suppression. The injection locked laser regenerator provides modulation format and wavelength transparency and can handle signals up to 25 Gbaud/s.

Finally, the injection locked laser is proposed as an additional unit at the input of the DPSK part of the DPSK/ASK receiver allowing the usage of higher ER of the ASK data stream, reaching the value of 8 dB, improving the total performance of the DPSK/ASK signal and therefore enabling its use as a cost effective alternative for channel capacity enhancement for access and metro networks.

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