

Phase synchronization scheme for a practical phase sensitive amplifier of ASK-NRZ signals

Stylianos Sygletos,^{1,*} Selwan K. Ibrahim,¹ Ruwan Weerasuriya,¹ Richard Phelan,² L. Grüner Nielsen,³ Adonis Bogris,^{4,5} Dimitris Syvridis,⁵ James O’Gorman,^{2,6} and Andrew D. Ellis¹

¹Tyndall National Institute and Department of Physics, University College Cork, Ireland

²Eblana Photonics, Trinity College Enterprise Centre, Pearse Street, Dublin 2, Ireland

³OFS Fitel, Prioparken 680, 2605 Brøndby, Denmark

⁴Department of Informatics, Technological Educational Institute of Athens, Aghiou Spiridonos, 12210, Athens

⁵National and Kapodistrian University of Athens, Panepistimioupolis, Illisia, Athens, GR-15784, Greece

⁶Xylophone Optics Ltd. 28, Orchardstown Drive, Rathfamham, Dublin 14, Ireland

*stylianos.sygletos@tyndall.ie

Abstract: We present a phase locking scheme that enables the demonstration of a practical dual pump degenerate phase sensitive amplifier for 10 Gbit/s non-return to zero amplitude shift keying signals. The scheme makes use of cascaded Mach Zehnder modulators for creating the pump frequencies as well as of injection locking for extracting the signal carrier and synchronizing the local lasers. An in depth optimization study has been performed, based on measured error rate performance, and the main degradation factors have been identified.

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OCIS codes: (190.4223) Nonlinear wave mixing; (250.4480) Optical amplifiers.

References and links

1. C. M. Caves, “Quantum limits on noise in linear amplifiers,” *Phys. Rev. D Part. Fields* **26**(8), 1817–1839 (1982).
2. A. Bogris, and D. Syvridis, “RZ-DPSK Signal Regeneration Based on Dual-Pump Phase-Sensitive Amplification in Fibers,” *IEEE Photon. Technol. Lett.* **18**(20), 2144–2146 (2006).
3. K. Croussore, and G. Li, “Phase and amplitude regeneration of differential phase-shift keyed signals using phase-sensitive amplification,” *IEEE J.Sel., Top. Quantum Electron.* **14**(3), 648–658 (2008).
4. C. J. McKinstrie, and S. Radic, “Phase-sensitive amplification in a fiber,” *Opt. Express* **12**(20), 4973–4979 (2004).
5. S. Ibrahim, S. Sygletos, R. Weerasuriya, and A. Ellis, “Novel carrier extraction scheme for phase modulated signals using feed-forward based modulation stripping,” in *Proc ECOC, We7. A4* (2010).
6. I. Kim, and K. Croussore, “Xiaoxu Li, Guifang Li, “All-optical carrier synchronization using a phase sensitive oscillator,” *IEEE Photon. Technol. Lett.* **19**(13), 987–989 (2007).
7. R. Weerasuriya, S. Sygletos, S. K. Ibrahim, R. Phelan, J. O’Carroll, B. Kelly, J. O’Gorman, and A. D. Ellis, “Generation of frequency symmetric signals from a BPSK input for phase sensitive amplification,” in *Proc. OFC 2010, OWT6, San Diego CA, USA, 21–25 March 2010*.
8. R. Slavik, F. Parmigiani, J. Kakande, C. Lundström, M. Sjödin, P. A. Andrekson, R. Weerasuriya, S. Sygletos, A. D. Ellis, L. Grüner-Nielsen, D. Jakobsen, S. Herstrøm, R. Phelan, J. O’Gorman, A. Bogris, D. Syvridis, S. Dasgupta, P. Petropoulos, and D. J. Richardson, “All-optical phase and amplitude regenerator for next-generation telecommunications systems,” *Nat. Photonics* **4**(10), 690–695 (2010).
9. J. Kakande, A. Bogris, R. Slavik, F. Parmigiani, D. Syvridis, P. Petropoulos, D. J. Richardson, “First demonstration of all-optical QPSK signal regeneration in a novel multi-format phase sensitive amplifier,” *ECOC 2010 Turin 19–23, PD 3.3, Sept* (2010).
10. S. Sygletos, R. Weerasuriya, S. Ibrahim, F. Gunning, A. Ellis, R. Phelan, J. O’Gorman, J. O’Carroll, B. Kelly, “A novel method of pump and idler signal generation for non-degenerate FWM based phase sensitive amplification,” in *Proc CLEO, CtuM5* (2010).
11. T. Healy, F. C. Gunning, A. D. Ellis, and J. D. Bull, “Multi-wavelength source using low drive-voltage amplitude modulators for optical communications,” *Opt Express* **15**(6), 2981–2986 (2007).
12. J. M. Kahn, “1 Gbit/s PSK homodyne transmission system using phase locked semiconductor lasers,” *IEEE Photon. Technol. Lett.* **1**(10), 340–342 (1989).
13. C. H. Henry, N. A. Olsson, and N. K. Dutta, “Locking range and stability of injection locked 1.54 μ m InGaAsP semiconductor laser,” *IEEE J. Quantum Electron.* **21**(8), 1152–1156 (1985).
14. A. C. Bordonalli, C. Walton, and A. J. Seeds, “High performance locking of wide linewidth semiconductor lasers by combined use of optical injection locking and optical-phase lock loop,” *J. Lightwave Technol.* **17**(2), 328–342 (1999).

15. W. Imajuku, and A. Takada, "In-line optical phase-sensitive amplifier with pump light source controlled by optical phase locked loop," *IEEE J. Lightwave Technol.* **17**(4), 637–646 (1999).
16. A. Takada, and W. Imajuku, "In-line phase-sensitive amplifier employing pump laser injection-locked to input signal light," *Electron. Lett.* **34**(3), 274–275 (1998).
17. J. Pezeshki, M. Saylor, H. Mandelberg, and J. Goldhar, "Generation of a cw local oscillator signal using a stabilized injection locked semiconductor laser," *IEEE J. Lightwave Technol.* **26**(5), 588–599 (2008).
18. A. S. Tistomo, and S. Gee, "Laser frequency fixation by multimode optical injection locking," *Opt. Express* **19**(2), 1081–1090 (2011).
19. M. J. Fice, and A. J. Seeds, "Frequency-selective homodyne coherent receiver with an optical injection phase lock loop," *Proc. OFC 2008, OWT1* (2008).
20. S. K. Ibrahim, S. Sygletos, R. Weerasuriya, and A. D. Ellis, "Novel real-time homodyne coherent receiver using a feed-forward based carrier extraction scheme for phase modulated signals," *Opt Express* **19**(9), 8320–8326 (2011).
21. O. Lidoyne, P. Gallion, and D. Erasme, "Analysis of a homodyne receiver using an injection-locked semiconductor laser," *IEEE J. Lightwave Technol.* **9**(5), 659–665 (1991).
22. E. K. Lau, L. J. Wong, X. Zhao, Y.-K. Chen, C. J. Chang-Hasnain, and M. C. Wu, "Bandwidth enhancement by master modulation of optical injection-locked lasers," *IEEE J. Lightwave Technol.* **26**(15), 2584–2593 (2008).
23. C.-C. Lin, Y.-C. Chi, H.-C. Kuo, P.-C. Peng, C. J. Chang-Hasnain, and G.-R. Lin, "Beyond-bandwidth electrical pulse modulation of a TO-Can packaged VCSEL for 10 Gbit/s injection locked NRZ-to-RZ transmission," *IEEE J. Lightwave Technol.* **29**, 830–841 (2011).
24. S. Osborne, K. Buckley, A. Amann, and S. O'Brien, "All-optical memory based on the injection locking bistability of a two-color laser diode," *Opt. Express* **17**(8), 6293–6300 (2009).
25. C.-H. Chen, S. Matsuo, K. Nozaki, A. Shinya, T. Sato, Y. Kawaguchi, H. Sumikura, and M. Notomi, "All-optical memory based on injection-locking bistability in photonic crystal lasers," *Opt. Express* **19**(4), 3387–3395 (2011).
26. S. Sygletos, *et al.*, "Dual pump wave generation from ASK-NRZ signal enabling a "black-box" phase sensitive amplifier" in *Proc. OFC 2011, OWL7*, Los Angeles CA, USA, 06–10 March 2011.

1. Introduction

Optical phase sensitive amplifiers (PSA) have become a topic of intense research activity due to their potential for low noise figures [1] and their ability to provide noise suppression both in the amplitude and phase of the optical signal [2–4]. As those properties have been well investigated in literature, the challenge for the actual deployment of PSAs in real networks is to make them self-contained, "black-box", elements in transmission links. Normally, this can be achieved by adding a synchronization stage to the PSA that will allow phase locking of its local pumps to the incoming signal. Although, the exact structure of this unit will depend on the specific four wave mixing (FWM) scheme employed by the PSA, as well as, on the modulation format of the transmitted signal, three basic functionalities might be in general required. The first is the recovery of the carrier, through a modulation stripping process [5,6]. The extracted carrier will be used as a reference for the phase synchronization of the local lasers. For PSA schemes that are not pumped at the signal frequency an additional frequency generation mechanism will be necessary to replicate the extracted carrier at the required locations. Simultaneous carrier extraction and frequency generation has been achieved through FWM of the incoming signal with one of the local pumps of the PSA in a highly nonlinear fiber [7]. This technique enabled the demonstration of the first black-box PSA with amplitude and phase regenerative properties for DPSK signals at 40 Gbit/s [8]. A more advanced FWM scheme in HNLF has also allowed the implementation of a practical PSA based regenerator for QPSK signals [9]. An alternative, compact and more power efficient approach for frequency generation in PSAs has been proposed in [10] based on the use of two cascaded Mach-Zehnder modulators (MZM) [11].

The phase locking of the local lasers to the extracted carriers is the last functionality of the synchronization unit before the phase sensitive amplification. This can be achieved either by an optical phase locked loops (OPLLs) [12] or through optical injection locking (OIL) [13,14]. Both techniques have been used in the earlier demonstrations of inline PSAs [15,16]. OPLLs suffer from a strict trade-off between laser linewidth and loop bandwidth, which prohibits low phase error operation with commercial off-the-shelf components [14,17]. On the other hand, OIL has been identified as a stable and reliable locking mechanism for laser synchronization [17], addressing a broad spectrum of applications that range from analog coherent detection [19–21] and direct modulation [22,23] to phase sensitive amplification [8,9] and all-optical digital storage [24,25]. However, although the physical properties of

optical injection locking have been well investigated, the limitations that it imposes on the actual performance of black box PSAs have not been yet fully explored.

In this paper we develop a phase locking scheme for the realization of the first dual pump degenerate black-box PSA for 10 Gbit/s non-return to zero amplitude shift keying ASK-NRZ signals [26]. The scheme makes use of an MZM based optical comb for frequency generation and two injection locking stages for carrier extraction and pump generation, respectively. Low bit error rates (BER) and receiver sensitivity penalties have been achieved for our system over a large power dynamic range and against optical signal to noise ratio (OSNR) degradations at the input to the PSA [26]. Furthermore, a detailed characterization of the transfer function properties of the local lasers, when they are injection locked by a modulated optical signal, revealed the main degradation mechanisms and indicated the optimum operating conditions of our scheme.

2. Principle and experiment setup

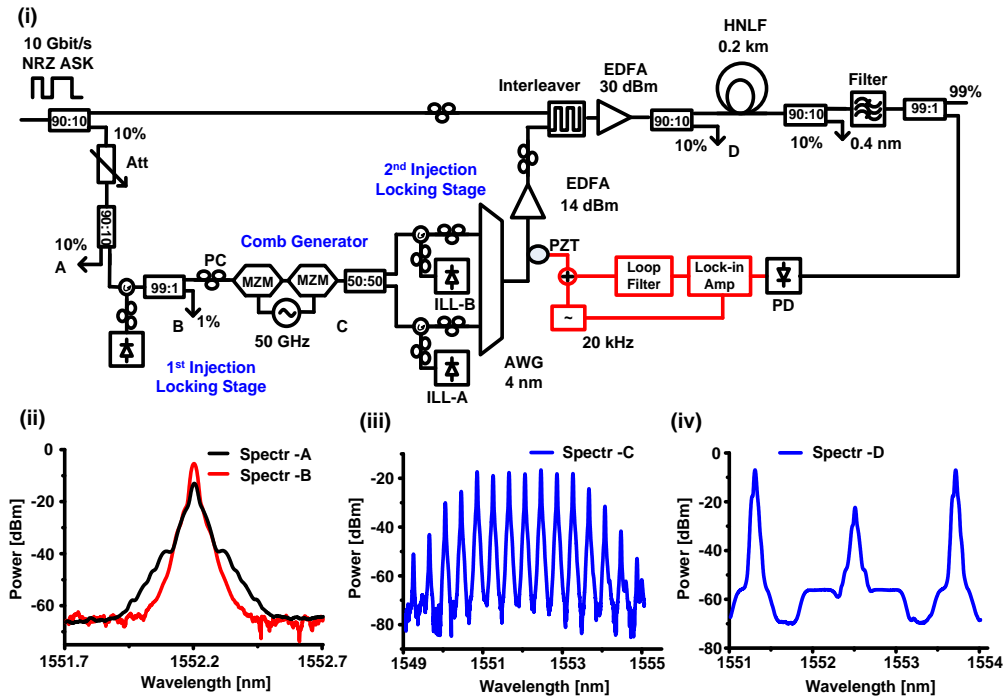


Fig. 1. (i) Experimental implementation of the proposed phase locking setup. (ii) Optical spectrum of the incoming ASK signal at point A (Spectr.-A) and the generated carrier after the 1st injection locking stage at point B (Spectr.-B). (iii) Spectrum of the generated comb signal at point C. (iv) Spectrum consisting of the generated phase synchronized pumps and the 10 Gbit/s ASK signal before the PSA, taken at point D.

The experimental setup of the proposed scheme is illustrated in Fig. 1(i). A 10 Gbit/s NRZ-ASK signal, with a pseudorandom bit sequence (PRBS) pattern length of $2^{31}-1$ and a controlled optical signal to noise ratio (OSNR), was launched at the regenerator input. To minimize the insertion loss, and hence the net noise figure of the PSA only the 10% of this was used as a reference for generating the local pumps of the PSA, while the remaining 90% was directed to the phase sensitive amplification stage. Pump generation was performed in three stages. In the first stage, a modulation stripping process took place to extract the signal carrier. For carrier-less formatted signals i.e. binary phase shift keying (BPSK), advanced nonlinear techniques would be required [6,7] for the carrier extraction. However, in our case the (NRZ-ASK) signal had already a carrier. Therefore, through optical injection locking with a local laser oscillator we could suppress amplitude modulation of the incoming waveform

and generate a pure and synchronized in phase cw-wave [21]. The corresponding optical spectra of the incoming ASK signal and the generated carrier after this injection locking stage, at points A and B respectively, are illustrated in Fig. 1(ii).

The next step was a frequency generation process that replicated the resulted signal carrier at the frequencies required for pumping the PSA. This was achieved using an opto-electronic comb generator that consisted of two balanced Mach-Zehnder amplitude modulators (MZMs) driven with sine waves at 50 GHz [11]. Each modulator produced a series of sidebands offset from the input frequency by an integer multiple of the drive frequency, see Fig. 1(iii). By carefully adjusting the modulator bias and the phase between the drive signals we could selectively suppress the amplitude level of one or more comb lines.

The comb generation inevitably reduced the signal power of the resultant carriers, making them inappropriate for direct use as pump waves in high performance PSAs since their OSNR would be significantly degraded by any subsequent amplifier used to obtain the required pump power level. To resolve this we used a 2nd injection locking stage. This stage selected two copies of the signal carrier at the required frequency shift and produced two CW-waves for dual pumping the PSA. The emitted power of each pump was 2 dBm. Both waves were combined by an arrayed waveguide grating (AWG) filter (0.4 nm) and then amplified by an EDFA to 14 dBm. Subsequently, the two amplified pumps were combined with the initial signal via a 50 GHz inter-leaver and after being amplified by a second EDFA to a total power of 30 dBm they were directed to the highly non-linear fiber (HNLF), see Fig. 1(iv). In the specific implementation, although the inline amplification is expected to jeopardize the sub-3dB noise figure potential of our PSA, it was required to maximize the power of the pump signals before HNLF for achieving phase sensitive gain performance. With high pump local lasers this pre-amplification stage could have been omitted. The HNLF fiber was a strained aluminous-silicate highly nonlinear fiber whose increased stimulated brillouin scattering (SBS) threshold alleviates the need for active SBS suppression. The fiber length was 210 m, the dispersion -0.20 ps/(nm·km), the nonlinear coefficient 7.4 W⁻¹km⁻¹ and the attenuation 14 dB/km at 1550 nm. The amplified signal was separated from the two pumps by a 0.4 nm bandwidth optical filter, and 1% of it was used as control signal for a piezoelectric fiber stretcher (PZT) based phase locking unit to mitigate the temperature induced phase changes.

3. Results

The ability of the proposed scheme to generate coherent local pumps from an incoming ASK signal is demonstrated in the results of Fig. 2(i)-(iii). More specifically, we measured the linewidth of the local pumps ILL-A and ILL-B when they are free running and when they are injection locked by the signal carrier, respectively. The corresponding RF traces, taken after a self-heterodyne setup used for this linewidth measurement, are demonstrated in Fig. 2(i). The free running linewidth was 7 MHz for both lasers. When the lasers were injection locked their linewidth was reduced to that of the signal carrier (~ 450 kHz), which indicated the achieved coherency. After this frequency synchronization process the overall system presented phase sensitive performance. In that case, its gain was governed by the relative phase $\varphi_{\text{rel}} = 2\varphi_s - \varphi_{p1} - \varphi_{p2}$ among the three interacting waves, where φ_s and φ_{p1} , φ_{p2} the absolute phases of the signal and the two pump waves, respectively. Using the PZT-based feedback circuit we could control φ_{rel} to achieve operation either at the maximum or at the minimum gain state of the PSA. Figure 2(ii) shows the corresponding optical spectra of the ASK signal at the output of the PSA. The contrast ratio of the two gain states was measured for different power levels entering the PSA, see Fig. 2(iii). At low input powers the PSA presents a contrast ratio of ~ 12 dB, however, for signal powers larger than 0 dBm the PSA became saturated and the contrast ratio dropped below 10 dB.

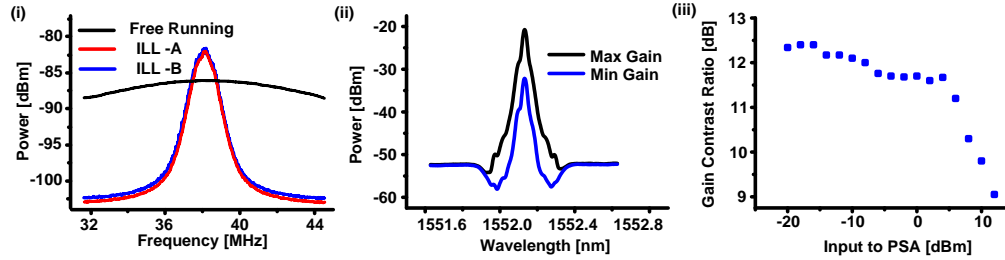


Fig. 2. (i) RF spectra of the two local pump lasers, ILL-A and ILL-B, of the PSA synchronization stage when free running and injection locked by the signal carrier, respectively. (ii) Optical spectra of output signal at minimum and maximum gain of the PSA, respectively. (iii) Contrast ratio of the PSA gain as a function of the input signal power.

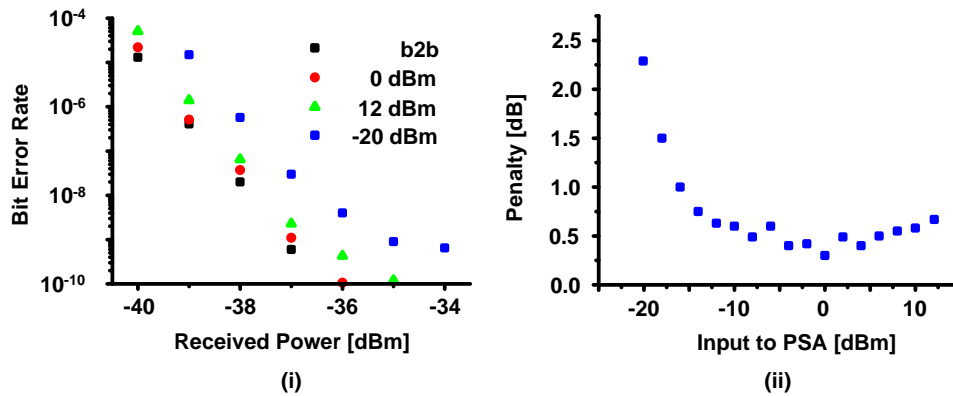


Fig. 3. (i) BER vs. received power at the output of the PSA for different input power levels at its input. (ii) Receiver sensitivity penalty as a function of the input power to the PSA.

Subsequently, we evaluated the performance of the proposed phase locking scheme by measuring the bit-error-rate BER of the signal at the output of the PSA. Figure 3(i) depicts the corresponding BER results versus received power, taken for different power levels at the input of the PSA. Comparing to the back-to-back case, also shown in Fig. 3(i), a receiver sensitivity penalty of less than 0.5 dB was achieved when the input power was 0 dBm. With an input power of 12 dBm the PSA operated in deep saturation, where strong interaction of the ASK modulated input signal with the pumps took place. As a result the sensitivity penalty increased to 0.7 dB. On the other hand, for an input power of -20 dBm, the receiver sensitivity penalty was 2.2 dB. This was due to the fact that the ASK signal became more vulnerable to the ASE noise induced by the 14 dBm EDFA which pre-amplified the pumps. Figure 3(ii) depicts measurements of the receiver sensitivity penalty, for different power levels entering the PSA. For a maximum allowed penalty of 1 dB our system presented power dynamic range of 30 dB.

In a real system, the injected power required by the first ILL, is expected to define the dynamic range of the PSA system and for the foregoing measurements, this parameter was fixed at -32 dBm. In Fig. 4(i), their injected power was varied and the corresponding changes in sensitivity penalty are shown, with the PSA input power level fixed at 0 dBm. The minimum power required for stable locking was -40 dBm, whereas to maintain the amplification penalty below 1 dB an injected power below -24 dBm was required. Above that level the power penalty increased rapidly. To identify the origin of this degradation we characterized the response of the injection locked lasers to a small signal modulation in the amplitude or phase of the injected optical signal [22]. Figure 4(ii) depicts the amplitude to amplitude (AM-to-AM) transfer function of the injection locked laser, located at the first

stage of our setup, see Fig. 1(i). Significant suppression of the input modulation is noticed, as well as a resonance peak at approximately 10 GHz. For injected power of -34 dBm the suppression at the resonant frequency exceeded 25 dB, whilst it became significantly stronger, approaching 40 dB, for lower modulation frequencies or lower injected powers. Since the same amount of suppression would be introduced at the 2nd injection locking stage any residual amplitude modulation on the generated pumps didn't affect the performance of the PSA.

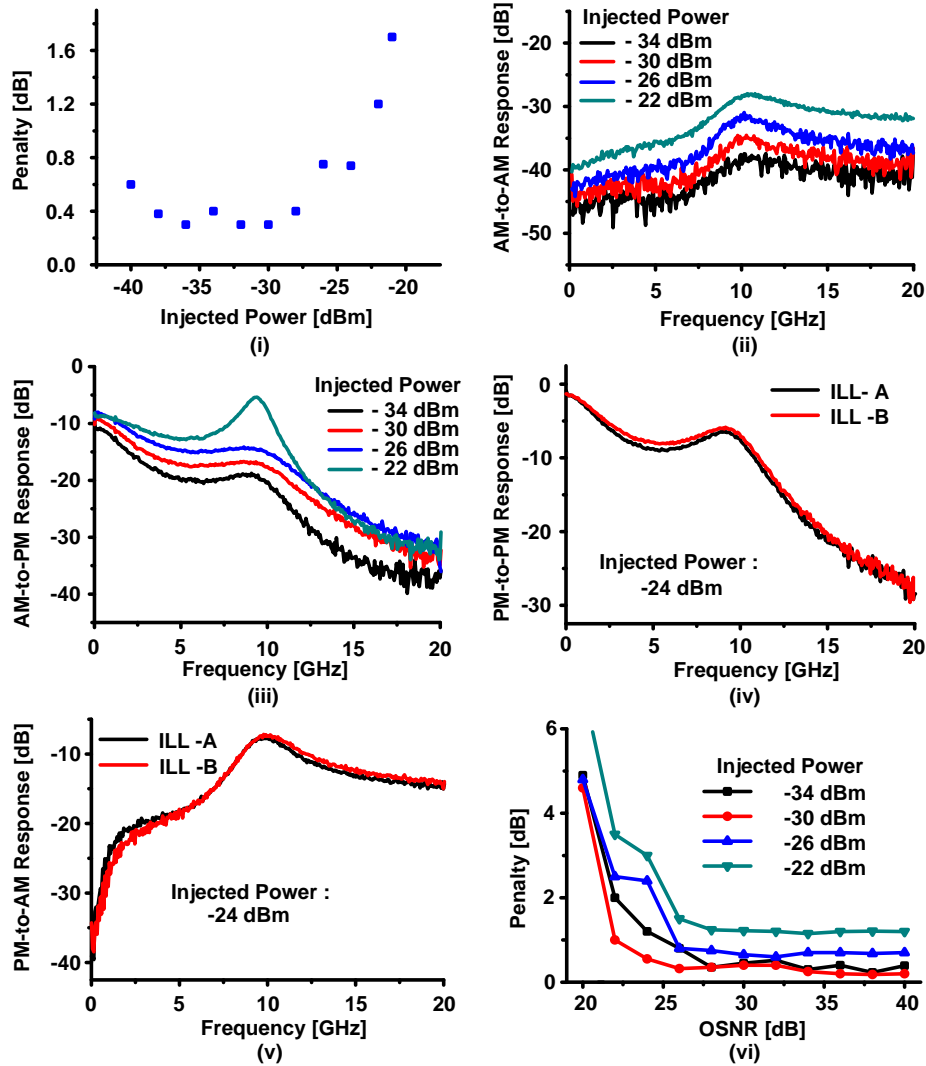


Fig. 4. (i) Receiver sensitivity penalty as a function of the injected power in the 1st injection locked laser. (ii) AM-to-AM transfer function of the 1st injection locked laser (iii) AM-to-PM transfer function of the 1st injection locked laser for different input power levels. (iv) PM-to-PM and (v) PM-to-AM transfer functions of the two pump lasers, ILL-A and ILL-B, of the synchronization scheme characterized at the operating power of -24 dBm. (vi) Receiver sensitivity penalty versus input OSNR for different injected powers to the 1st ILL.

On the other hand, due to the laser's linewidth enhancement factor, carrier density variations caused by amplitude modulations on the injected signal are translated to phase modulation at the output. Figure 4(iii) shows the measured amplitude to phase (AM-to-PM) transfer function of the 1st injection locked laser for different input power levels. The transfer

function is low pass with frequencies below 1 GHz experiencing an attenuation of around 10 dB. The attenuation increases rapidly at higher frequencies for injected powers less than -26 dBm, but a strong frequency resonance appears at 10 GHz for powers larger than -22 dBm. This resonance should coincide with intrinsic relaxation oscillation frequency of the slave laser provided that low injection levels are not expected to change the oscillation properties of the slave. Compared to the AM-to-AM case, it is clear that the AM-to-PM conversion is stronger giving rise to phase distortions that might limit the performance of our system. Therefore, to identify the purity of the generated pumps, the phase to phase (PM-to-PM) and phase to amplitude (PM-to-AM) conversions at the 2nd injection locking stage were also measured. The corresponding transfer functions are illustrated in Fig. 4(iv) and Fig. 4(v), respectively. Both of them have been taken for an input power of -24 dBm. The PM-to-PM response is low pass, where frequencies below 1 GHz are attenuated by only 3 dB. These results indicate that phase distortions, created by the carrier extraction process at the 1st injection locking stage, are transferred through the 2nd injection locking stage to the pump signals and could degrade the performance of the PSA if the input signal power is not carefully controlled.

Results of the sensitivity penalty as a function of the input OSNR degradation are presented in Fig. 4(vi). The measurements have been taken also for different injected powers into the 1st ILL. The optimum power level was approximately -30 dBm, and to keep the penalty below 1 dB the OSNR should be maintained above 22dB.

Finally, in Fig. 5 the eye diagrams at the output of the PSA for different injected power levels are presented. The OSNR at the input of the PSA was 24 dB. It is shown that all of the eye diagrams were open, which proves the low penalty performance of our scheme.

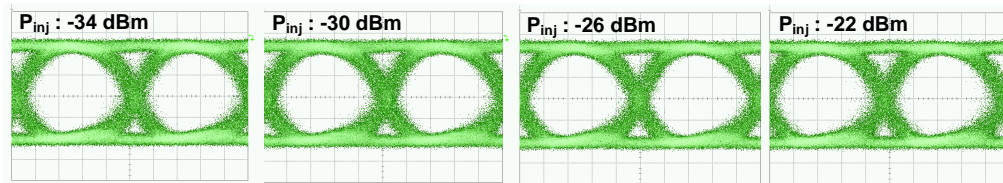


Fig. 5. Eye diagrams at the output of the PSA for different injected powers to the 1st injection locked laser. The input OSNR level was 24 dB

4. Conclusions

We have reported a novel phase locking scheme and developed a black-box PSA for NRZ-ASK signals at 10 Gbit/s. Optimization based on measured error rate performance has been carried out and the main degradation mechanisms have been investigated. The scheme necessitated the use of two cascaded injection locking stages to suppress sufficiently the amplitude modulation of the input ASK signal for generating high quality pumps. In particular, measurements of the transfer function response of the injection locked lasers to a modulated optical signal revealed the existence of a strong amplitude-to-phase conversion mechanism, which created a residual modulation in the phase of the extracted carrier. This modulation passed unsuppressed through the second injection locking stage destroying the quality of the synchronized pumps, and degrading the performance of the PSA. Operation at low injected power levels (~ 30 dBm) mitigated the influence of this mechanism and ensured low bit error rate performance. However, as at those conditions the injection locking area has a width of only several hundreds of MHz, to maintain long term stability the temperature and the driving current of the signal and the local lasers of the PSA should be efficiently controlled to avoid wavelength drifts. Finally, further characterization of our system demonstrated low sensitivity penalty (< 1 dB) over a large operating region and robustness against input OSNR degradations.

Acknowledgments

This work has been supported and by European Communities Seventh Framework Programme FP/2007-2013 under grant agreement 224547 (PHASORS) and by Science Foundation Ireland under Grant 06/IN/I969.