Dual Pump Wave Generation from NRZ-ASK Signal Enabling a "Black-Box" Phase Sensitive Amplifier

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Abstract: We present a phase locking scheme that enables the demonstration of the first black-box dual pump degenerate phase sensitive amplifier for 10 Gbit/s NRZ-ASK signals.

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1. Introduction

Optical phase sensitive amplification (PSA) has become a topic of intense research activity due to its potential for advanced noise figure performance [1] and its ability to provide noise suppression both in the amplitude and phase of the propagating signal [2],[3]. As those properties have been well investigated in the literature, the challenge for the actual deployment of this technology in real networks is to enable phase sensitive amplifiers (PSAs) to become self-contained, "black-box", elements in a transmission link. Normally, this can be achieved through appropriate phase synchronization circuits that create synchronized pump and idler waves from the incoming signal. In cases where the interacting waves are of the same wavelength, i.e. in single pump degenerate FWM schemes, traditional schemes such as optical phase locked loop [4] or injection locking [5] have been proposed for the phase synchronization. In all the other cases, i.e. in dual pump degenerate or in single/dual pump non-degenerate schemes, a phase insensitive fiber optic parametric amplifier (PI-FOPA) has been proposed to prepare the required frequency and phase matching conditions among the interacting waves [6],[7],[8]. Based on this technique, different realizations of "black-box" PSAs have been developed for D(Q)PSK signal formats [9],[10]. An alternative phase locking approach, for "black-box" PSAs has been presented in [11]. This scheme makes use of two cascaded Mach Zehnder modulators (MZM) for optical comb generation and of injection locking to create the phase synchronized waves, therefore, it can be considered as more power efficient and compact.

In this paper we extend the concept presented in [11] and develop a more advanced phase locking scheme for the realization of the first dual pump degenerate "black-box" PSA for 10 Gbit/s NRZ-ASK signals. The new scheme, apart from the MZM based optical comb, makes use of two injection locking stages for carrier extraction and pump generation, respectively. Low bit error rates (BER) and receiver sensitivity penalty performance have been achieved for our system whilst detailed characterization revealed robust operation over a large power dynamic range and against optical signal to noise ratio (OSNR) degradations at the input to the PSA.

2. Experimental Setup

The experimental setup of the proposed scheme is illustrated in Fig. 1(i). A 10 Gbit/s NRZ-ASK signal with a pseudo random bit sequence (PRBS) pattern length of 2^{31}-1 and a controlled optical signal to noise ratio (OSNR) was presented to the regenerator input. To minimize the insertion loss, and hence the net noise figure of the PSA, only 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, we applied a modulation stripping process to extract the signal carrier. For carrier-less modulation formats i.e. BPSK, a preliminary data stripping module would be required [12],[13], however in our case the NRZ-ASK signal already had a carrier, and thus optical injection locking was used to suppress amplitude modulation of the incoming waveform and generate a pure and synchronized in-phase cw-wave [14]. The corresponding optical spectrums of the incoming ASK signal and the generated carrier after this injection locking stage, taken at points A and B respectively, are illustrated in Fig. 1(ii).

The cw signal was then passed through an opto-electronic comb generator comprising two balanced MZMs driven with sine waves at 50 GHz [15]. 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 the amplitude level of specific comb lines could be optimized.

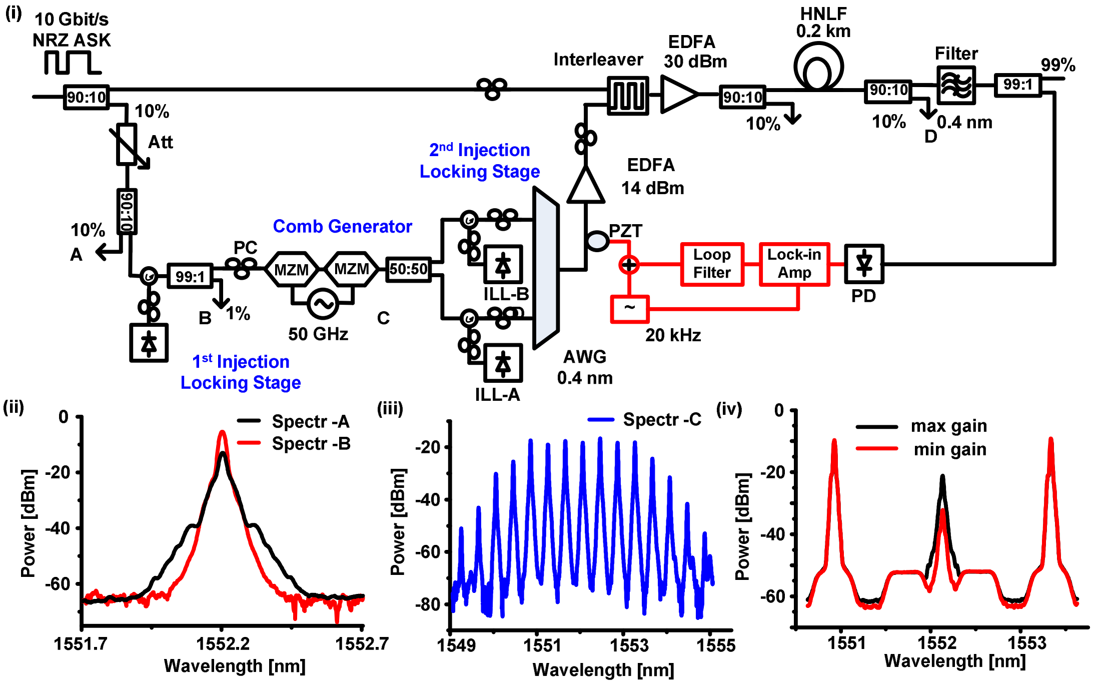

Fig.1 (i) Experimental implementation of the proposed phase locking setup. (ii) Optical spectrum of the incoming ASK signal at point A (Spectr. –A) and the generated carrier after the 1st injection locking stage at point B (Spectr. –B). (iii) Spectrum of the generated comb at point C. (iv) Spectrum of the ASK signal and the pumps, at the output of the HLNF (point D) taken for maximum and minimum PSA gains.

The comb generation inevitably reduced the signal power of the resultant carriers, making them inappropriate for direct use as pumps 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 AWG filter with a 0.4 nm channel bandwidth 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 nonlinear fibre (HNLF). With enhanced design of the HNLF fiber and injection locked lasers (ILL) with higher output power would enable one or more of these pre-amplification stages to be omitted. The HNLF fibre used in this experiment was a strained aluminous-silicate highly nonlinear fiber whose increased stimulated brillouin scattering (SBS) threshold alleviated the need for active SBS suppression at 1550 nm. The fibre length was 210 m, the dispersion -0.20 ps/(nm·km), the nonlinear coefficient 7.4 $W^{-1}km^{-1}$ and the attenuation 14 dB/km. The phase sensitive gain at the output of the HNLF, demonstrated a contrast ratio of ~12 dB, see Fig. 1(iv). The amplified signal was separated from the two pumps by a 0.4 nm bandwidth optical filter, and 1% of it was used as the control signal for a piezoelectric fibre stretcher based phase locking unit to mitigate the slow temperature induced phase changes.

3. Results

Fig. 2(i) depicts bit error rate (BER) measurements versus received power, taken at the output of the PSA, for different power levels at its input. Comparing with the back-to-back case, also shown in Fig. 2(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 and the sensitivity penalty increased to 0.7 dB. For an input power of -20 dBm the receiver sensitivity penalty approached 2.2 dB. This is due to the fact that the ASK signal becomes more vulnerable to the ASE noise loaded by the 14 dBm EDFA which pre-amplifies the pumps. Fig. 2(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 presents a power dynamic range which approaches 30 dB.

In a real system, the injected power required by the first ILL, is expected to play a crucial role in defining the dynamic range of the PSA system and for the foregoing measurements, this parameter was fixed at -32 dBm. In Fig. 2(iii), the 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 amplitude suppression capabilities of the injection locking process become less effective and its amplitude-to-phase conversion mechanism is significantly enhanced [16]. These factors would create pump phase distortions that would limit the performance of the "black-box" PSA. Results of the sensitivity penalty as a function of the input OSNR degradation are presented in Fig. 2(iv). The measurements have been taken also for different injected powers to 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.

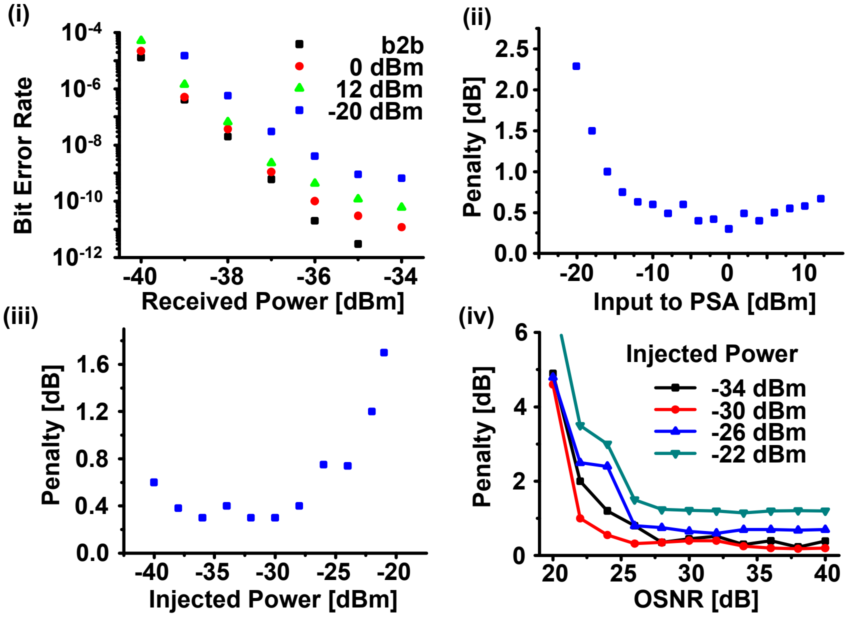

Fig.2 (i) BER vs. received power at the output of the PSA for different input power levels at its input. (ii) Receiver sensitivity penalty as a function of the input power to the PSA. (iii) Receiver sensitivity penalty as a function of the injected power to the 1st injection locked laser. (iv) Receiver sensitivity penalty versus input OSNR for different injected powers to the 1st ILL

Finally, in Fig. 3 the eye diagrams at the output of the PSA for different injected power levels are presented. They have been taken when the OSNR at the input of the PSA was 24 dB. All of them are open, which proves the low penalty performance of our scheme.

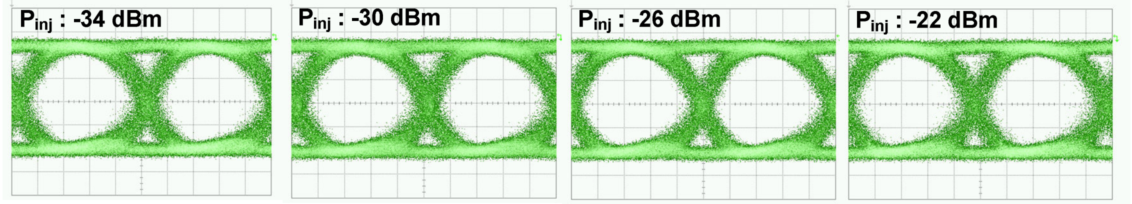

Fig.3 Eye diagrams at the out of the PSA for different injected powers to the 1st injection locked laser. The input OSNR level was 24 dB.

4. Conclusions

We have reported a novel phase locking scheme and the development of a "black-box" PSA for NRZ-ASK signals at 10 Gbit/s. Optimization based on measured error rate performance has been carried out revealing a low sensitivity penalty (< 1 dB) over a large operating region and robustness against input OSNR degradations.

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5. References

[1] C.M. Caves, *Phys. Rev.* D.**26**, 1817-1839 (1982)
[2] A. Bogris, D. Syvridis, *IEEE PTL*, **18**(20), 2144-2146 (2006).
[3] K. Croussore, G. F. Li, *IEEE JTSQE,* **14**(3), 648-658 (2008).
[4] W. Imajuku, A. Takada, *IEEE JLT,* **17**(3), 637-646 (1999).
[5] A. Takada, I. Imajuku, *Electr. Lett.* **34** (3), 274-276, (1998).
[6] C. J. McKinstrie, at al, *Opt Exp.* **12** (20) 4973-4979 (2004)
[7] R. Tang et. al., *Opt. Expr.* **13**(26) 10483-10493 (2005)
[8] R. Weerasuriya et al., *in Proc. OFC,* OWT6 (2010)
[9] F. Parmigiani et al., *in Proc OFC,* PDPC3 (2010)
[10] J. Kakande et.al., *in Proc. ECOC,* PD.3.3 (2010)
[11] S. Sygletos et al., *in Proc CLEO,* CtuM5 (2010)
[12] S. Ibrahim et al., *in Proc ECOC,* We7. A4 (2010)
[13] I. Kim et al., *IEEE PTL*, **19**(13), 2007
[14] O. Lidoyne et al., *IEEE JLT*, **9**(5), 1991
[15] T. Healy et al., *Opt. Expr.* **15**(6) 2981-2986 (2007)
[16] E. Lau et al., IEEE JLT **16**(15) 2584-2593 (2008)