Polarization-Independent Coherent Real-time Analog Receiver for PON Access Systems

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Abstract— **A 1.25 Gb/s ASK Passive Optical Network (PON) system with a –51dBm pre-FEC sensitivity (at BER=$2\cdot10^{-3}$) is enabled by a real-time polarization-independent coherent receiver (PI-RX) that needs no DSP (nor ADC). The receiver, which only makes use of common DFBs and commercially available electronic ICs, is targeted for use on a 6.25 GHz UD-WDM grid and has a 52 dB dynamic range. Measurements of the robustness of the PI-RX against back-reflections and crosstalk from coexistent adjacent channels show that this preliminary implementation is suitable for UD-WDM-PON systems with frequency spacing down to 5 GHz.**

***Index Terms*— Optical Access Network, Optical Communication Equipment, Optical Coherent Detection, Optical Fiber Communications, Optical Fiber Networks.**

I. INTRODUCTION

WITH the advent of 5G mobile technology, next generation access network are expected to support a huge and ever increasing traffic load[1]. The capacity increase should be obtained gradually and leveraging as much as possible on the existing network infrastructure, in order to be economically sustainable [2].

Recently, coherent optical technology has been introduced in metro and core networks, thanks to the key developments in electronic Digital Signal Processing (DSP) that takes advantage of newly available ultra-high speed Analog to Digital Converters (ADC's) and dedicated ASICs.[3]. It was then proposed that Coherent Wavelength Division Multiplexed (WDM) Passive Optical Network (PON) could also be developed for the optical access network segment [4]. These coherent PON systems might allow to achieve seamless upgrade of existing fiber plants, which are based on high-loss power splitters [5][4]. In fact, coherent systems have the potential to provide for increased power budget and also much higher channel density. However, these targets must be achieved with low-cost implementations of the receiver: i.e. it is not possible to directly transfer the expensive receiver architectures developed for the core network straight into the optical access. Various solutions have been already presented [6][7][8][9], based on external cavity lasers, and high-end ADCs and ASICs. These solutions make use of advanced modulation formats (including polarization multiplexing), powerful FEC and sophisticated DSP to mitigate linear and non linear impairments in order to achieve high power budgets and high spectral density (Ultra Dense WDM, UD-WDM). In this sense they are still shaped around the metro-core coherent paradigm. However we believe that it is necessary to develop new solutions that are specifically designed for optical access applications: these must be free from expensive photonic and/or electronic components, as suggested in [10][11]. In addition, some access applications have strict requirements on the latency, which is in favor of the removal (or drastic simplification) of DSP units [1].

The EU FP7 COCONUT project addresses this problem, aiming to demonstrate a λ-to-the-user UD-WDM PON approach by adopting a different paradigm, i.e., low cost, fully analogue optical coherent detection [12]. In this framework, we proposed a WDM-PON coherent system based on simple and effective ASK phase diversity-receiver [13], where a 3×3 symmetric coupler (120° hybrid) allows phase-diverse coherent detection based on a common DFB as local oscillator (LO), without complex frequency control, and considering use of a light FEC (7% overhead). Later on we also demonstrated theoretically [14] and experimentally [15] how the proposed simplified coherent receiver can be turned into a polarization independent receiver (PI-RX) not based on DSP [16] nor using polarization diversity [17] nor external polarization scramblers [18]. It rather exploits the third input of the coupler and uses intradyne operation [14]. In these experiments [15], however, signal demodulation was accomplished with offline processing in a Real Time Oscilloscope (RTO).

We recently presented the first real-time implementation of the proposed PI-RX, tested in a complete and realistic system experiment [19]. Here we give an expanded description of the real time PI-RX, realized by using off-the-shelf components, such as commercial Radio Frequency (RF) multipliers, amplifiers and combiners, without any DSP and expensive ADC's.

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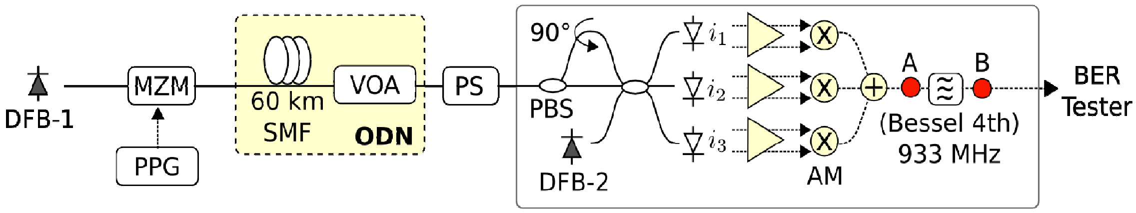

Fig. 1. Experimental set-up

Despite the very simple implementation based on discrete optical and electronic components, <–50 dBm pre-FEC sensitivity is obtained, which can sustain a very high loss of the Optical Distribution Network (ODN). These promising features show its potential as a candidate for future PON solutions.

The paper is organized as follows. In Section II the operating principle and the practical implementation of the PI-RX prototype is discussed. Section III presents the receiver characterization in terms of transmission performance, resilience to back-reflections, resilience to crosstalk of interfering channels and dynamic range. Finally, in Section IV we summarize the main results and draw some conclusions.

II. Receiver structure and experimental set-up

The structure of the proposed PI-RX is shown in fig. 1 where the complete experimental setup used for testing the PI-RX is also depicted, . Here, for simplicity, the transmitter (TX) was made of a common DFB (λ=1540.8 nm, < 10 MHz linewidth and <140 dB/Hz RIN) externally modulated by a Mach-Zehnder modulator (MZM), driven at 1.25 Gb/s by a PRBS sequence (2^{31}-1 bits long). Since the focus of this work is on the receiver performance, external modulation was used at the transmitter in order to isolate signal-related impairments. We already demonstrated, although with offline processing, that the RX can also work with directly modulated laser (DML) with similar performance [20].

The considered ODN consists of a 60 km single-mode fiber (SMF, G.652, 13 dB loss), a variable optical attenuator (VOA) emulating splitting loss, and a Polarization Scrambler (PS) producing random variations of the signal State of Polarization (SoP), in order to emulate a typical real world operating environment.

The schematic of the real-time PI-RX, is reported on the right of Fig. 1. At the RX input, the X and Y-polarization components of the signal are separated by a Polarizing Beam Splitter (PBS); the polarization of one of them is rotated by 90° so that they both enter with parallel SoP into a symmetrical 3×3 fused-fiber power coupler [14]. The Local Oscillator (LO) is injected in the 3rd input port of the coupler, with the same SoP as the two signal components. The light exiting the three output ports of the coupler is then sent to three nominally identical PIN photodetectors followed by Trans-Impedance Amplifiers (TIAs) with 2 GHz 3dB bandwidth and differential outputs. To make the optical circuit stable, all the used components and patch-cords in the RX were of the polarization maintaining type (including the 3×3 coupler). Care was exercised to equalize the three optical paths leading the signal and then the mixed signal to the photodetectors.

The LO (emitted power +3 dBm) is a common DFB with the same specs as the DFB in the TX. The LO wavelength is thermally tuned and controlled so as to work in intradyne regime with $\Delta\nu$=850 MHz ($\Delta\nu$: frequency difference between signal and LO). As theoretically demonstrated, for this type of PI-RX intradyne operation is needed to achieve polarization independence and the value of the detuning $\Delta\nu$ should be >70% of the bit-rate [14]. The above $\Delta\nu$ can be varied in a >100 MHz range without impairing the overall performance, as discussed later.

Once properly amplified, the obtained photocurrents feed three RF analogue multipliers (⊗ in Fig. 1), with 2 GHz operating bandwidth (starting from DC). Since we feed the multipliers with the differential current pairs, the squaring operation is effectively obtained on each photocurrent. To this aim the electrical response of the three multipliers must be as similar as possible. This is shown in Fig. 2, where the measured 2nd harmonic conversion efficiencies of the three devices as a function of the input frequency are reported. Identical results were obtained within experimental accuracy demonstrating that operation is uniform across the used devices.

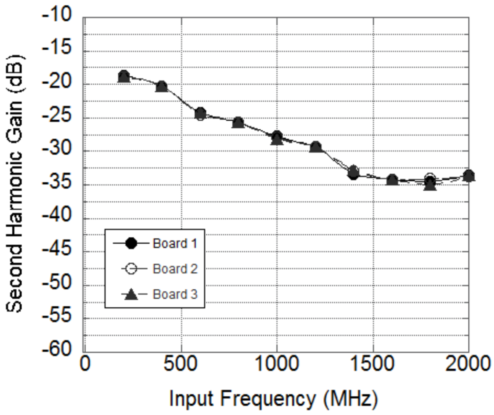

Fig. 2. Measured Second Harmonic gain of the three analog multipliers as a function of the input frequency (sinusoidal test signal, V_{pp}= 1 V).

The squared signals are finally summed by an electrical power combiner (⊕ in Fig. 1, bandwidth 18 GHz) to yield the recovered signal intensity [21][22]. The sum signal is then passed through a standard low-pass filter (LPF, Bessel 4th

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order -see Fig. 1- , 933 MHz bandwidth), as usual in a NRZ receiver.

In order to show how the PI-RX is actually working, we report in Fig. 3 the electrical spectra of the recovered signal before and after the LPF. Trace (a) shows the spectrum obtained when the signal SoP is aligned to that of the LO, which is a typical NRZ spectrum: here we also see a residual tone at frequency $\Delta\nu$ (in-band with the signal). This tone is due to a non-ideal behavior of the receiver components (e.g. not exact 120° phase shift within the 3x3 coupler, slightly different PIN responsivity, non-ideal frequency-response of the multipliers etc.). However, this spurious tone has very low amplitude thus it does not affect significantly the receiver performance.

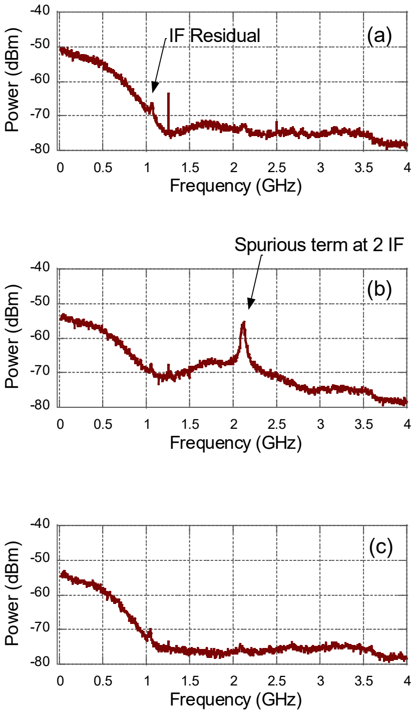

Fig. 3. Electrical spectra of the signal: a) at point A of Fig.1 with parallel signal-LO polarizations; b) at point A of Fig.1 with worst-case signal-LO polarizations (45°); c) at point B of Fig.1 (after the Bessel filter) with worst-case signal-LO polarizations.

Trace (b) shows the spectrum taken at point A in Fig. 1 when the SoP of the input signal is rotated by 45° with respect to the LO, which is the worst-case condition for the RX: here a spurious tone at $2\Delta\nu$ (which reaches maximum amplitude for this SoP) is observed, as expected [14]. This tone has significant amplitude and might impair the system. However, being at high frequency, it is effectively suppressed by the LPF, and a clear signal is indeed obtained at point B in Fig. 1. The corresponding electrical spectrum is shown in Fig. 2-c. Fig. 4 shows the eye diagrams taken after the LPF Bessel filter, when the input signal SoP is exactly aligned to that of the LO (signal coming out entirely from one output of the PBS) and when the SoP of the signal is set in the worst condition (signal coming out from the two outputs of the PBS with equal power). By comparing these two eye diagrams, minor differences are observed, namely in case b) the eye diagram shows thicker traces. As already pointed out, this has a very limited impact on the system performance (see next Section).

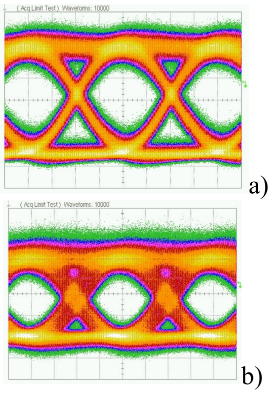

Fig. 4 Eye diagrams of PI-RX; a) best-case (signal and LO with parallel SoP); b) worst-case (signal power equally split by the PBS).

III. REAL-TIME RECEIVER CHARACTERIZATION

The proposed PI-RX performance was first characterized as a function of the signal input power. Figure 5 reports the results of BER measurements in various conditions. The back-to-back (B2B) measurements of the BER vs. input power when the signal has a parallel (black squares) or orthogonal (black triangles) SoP with respect to the LO clearly show that the receiver is actually polarization independent.

Moreover, a pre-FEC sensitivity of about −51 dBm (FEC level at BER=$2\cdot10^{-3}$) is obtained. No error floor is observed down to BER=10^{-10}. We see, however, that the two polarizations show a slightly different performance, likely due to a small difference of the insertion loss of the PBS (and connectors) at its two outputs.

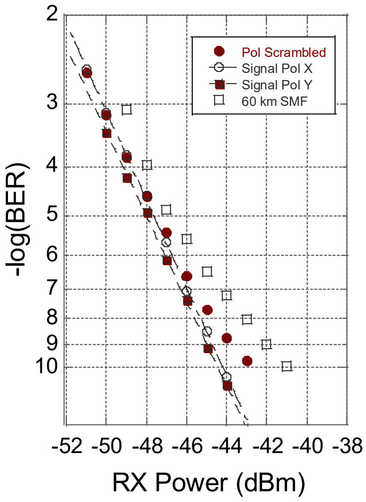

Fig. 5. Measured BER vs. received power curves in back-to-back and after transmission (white squares).

Then the PI-RX is put under stress by turning on the polarization scrambler (PS) in front of it (see Fig. 1). The scrambler randomly changes the signal SoP (at a frequency of 6 kHz) in a way to uniformly cover the Poincaré sphere. The measured BER curve is the one with black dots in Fig. 5. In this case, no penalty is observed at FEC level, but a penalty of about 1 dB arises at BER=10^{-9} where, nevertheless, we report the still remarkable sensitivity of –44 dBm. This penalty can be ascribed to the combined effect of the small differences in the insertion loss in the polarization paths (including connectors), small residual differences in the optical paths, non uniformity of the splitting ratio of the 3x3 coupler and to the excess jitter of the PI-RX in the worst signal SoP case (see eye diagram (b) of Fig. 4), as theoretically predicted in [14].

The used PBS has a measured extinction ratio > 27 dB across the whole C-band. We also verified experimentally that at the selected operating bitrate the precision on the patch-cord length should be ≤1 cm in order not to impair receiver performance. This problem can be automatically solved in a photonic integrated version of the optical front-end [22].

As far as the spectral uniformity of the splitting ratio of the PM 3x3 coupler is concerned, the transmittivity of the used coupler has been characterized port by port across the whole C band (1530-1560 nm) launching light at the operating polarization. The PM fused fiber 3×3 coupler resulted less spectrally uniform than a conventional one, for which typically the peak-to-peak observed transmittivity deviation with respect to 1/3 is below 10% (about 0.5 dB) across the C band and across the six ports. Nevertheless the performance of the receiver is quite good even though the operation wavelength is in a region were the coupler behaviour is not optimal.

As shown in [23] by means of extensive numerical simulations, the gain unbalance on the three channels of a 3x3 hybrid must be below 5% and and the angle mismatch of the three ports should be less than ±10° (equivalent to a splitting ratio deviation of about 20% with respect to the ideal value of 1/3) , in order to have penalties below 1 dB with respect to the ideal case. In our receiver the first condition is met whereas we think the second is hardly matched.

We note that a pre-FEC sensitivity of –51 dBm corresponds to an improvement of about 10 dB with respect to the specifications of commercially available direct-detection receivers (typical performance is described for example in [5]). Moreover, we stress that the measured BER curves shown here do actually match those taken with offline processing within the experimental error (±0.5 dB) down to around BER=10^{-6} (lowest BER value that we can reliably estimated by offline processing with our RTO).

Then, the transmission performance over a 60 km strand of SMF was tested. After SMF transmission (BER curve with white squares in Fig. 5), a penalty of about 2 dB at BER=10^{-9} is observed, which, we believe, can be reduced by further optimization of the components. We note that assuming a pre-FEC sensitivity of –49 dBm (as from Fig. 4 including optical path penalty) and a moderate launch power of 0 dBm, about 36 dB of loss budget still remains to be allotted after transmission in a 60 km fiber feeder. This excess loss budget can allow for a 1:512 splitting plus about 5 dB of system margin.

The pre-FEC B2B sensitivity of our receiver is 1 dB better than that of the single polarization ASK coherent system reported in [11] and is about 3 dB better than that of the receiver in [7], even though in [7] the modulation is QPSK and the receiver structure is more complex (90° hybrid, polarization diversity). The real-time receiver in [7] shows an error floor at BER=10^{-9}, whereas our receiver works well down to BER=10^{-10}. We note that the absence of error floors even at very low BER values is a feature that can be very useful for specialized applications having strict latency requirements, such as mobile front-hauling, were the use of FEC can be problematic.

Besides demonstration of the receiver functionality, it is also important to investigate the receiver resilience to system parameter variations and its robustness under the operation conditions that can be found in an actual UD-WDM PON. These are important features in view of the engineering of the receiver in possible pre-commercial prototypes.

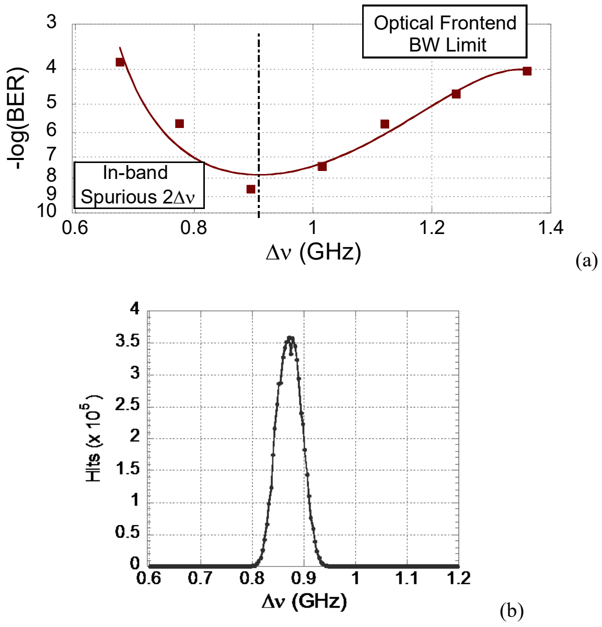

Fig. 6. a) Measured back-to-back BER vs. LO detuning at fixed received power (-44 dBm); b) Histogram of signal-LO frequency detuning measured over a 2h 30 m time lapse.

As discussed in Sect. II, the intradyne frequency detuning $\Delta\nu$ is a critical parameter for proper operation of the receiver. The PI-RX tolerance to deviations with respect to the ideal frequency setting has been measured at the received power of – 44 dBm where a strong sensitivity is expected due to the low BER. The results are shown in Fig. 6a. The receiver performance is maximum at the optimal intradyne frequency setting (about 900 MHz, BER=$2\cdot10^{-9}$) and a deviation of about ±100 MHz around the optimal setting can be tolerated without significant degradations even at such low BER levels. As can

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be inferred from the electrical spectra of Fig. 2, for lower detuning values the baseband signal is corrupted by spurious terms introduced by squaring (the lower the detuning the higher the impairment) whereas for higher detuning values the performance is bound by the PIN diodes bandwidth (the higher the detuning the higher the impairment).

Figure 6b shows the histogram of detuning fluctuations of the transmitter-LO DFB couple used in the experiments, taken over a 2h 30m interval in our lab (air-conditioned but not temperature stabilized). We note that the laser temperature is accurately controlled without feedback loops. Despite this, the measured FWHM width of the distribution is about 70 MHz, which reasonably ensures stable operation of the PI-TX for hours in a laboratory environment. For truly long term operation, a slow frequency drift compensator might be necessary.

Another important feature is the robustness of the coherent receiver against back-reflections and crosstalk from adjacent UD-WDM channels.

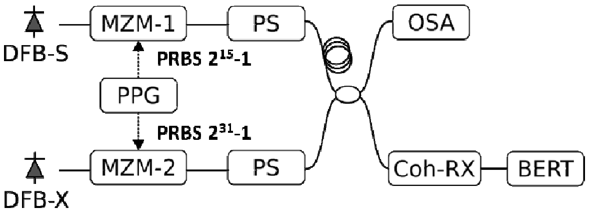

Fig. 7: Set-up for back-reflection and crosstalk measurements

To perform reflection and crosstalk measurements the set-up of Fig. 1 was modified as shown in Fig. 7, where a second transmitter was added to provide for an interfering channel. The second transmitter consists of a DFB laser (DFB-X), with same specs of the other involved lasers, tuned thermally to the desired frequency spacing. The light of DFB-S (signal source) and DFB-X was modulated at 1.25 Gbit/s by two MZMs driven by a PPG with two outputs. The PPG provides two independent data patterns of different length (2^{31}-1 for the signal modulation, and 2^{15}-1 for the interferer). The power of each transmitter was set by means of a VOA and then the two signals were coupled to the receiver input arm by means of a 50:50 coupler. To further de-correlate the data patterns of the two signals, a fiber strand of about a hundred meters was added in the interferer path. All the measurement were taken in a B2B configuration. A polarization scrambler was placed in each transmitter arm to average over polarization. The signal to interferer level and frequency spacing was controlled online by means of a high resolution Optical Spectrum Analyser (OSA) connected to the second output arm of the 50:50 coupler (frequency spacing was also checked in parallel using an electrical spectrum analyzer). In all measurements discussed below, we assumed a BER of $2{\cdot}10^{-3}$ (to which we will refer as FEC level, attained at the received power of –50.5 dBm) as a reference, in line with the use of a light FEC [24] and the power penalty with respect to this was measured to give a direct insight of the system impact.

In the following we consider the use of our PI-RX in PON system architectures with a 6.25 GHz channel granularity. A first example of such an architecture consists of a group of *N* UDWDM channels spaced 6.25 GHz in downstream and a similar group of *N* channels in upstream, in a different spectral region. Another example we can envisage considers the use of two 12.5 GHz UDWDM combs in the same spectral region, one for downstream transmission the other for upstream, interleaved so that the minimum channel spacing is 6.25 GHz.

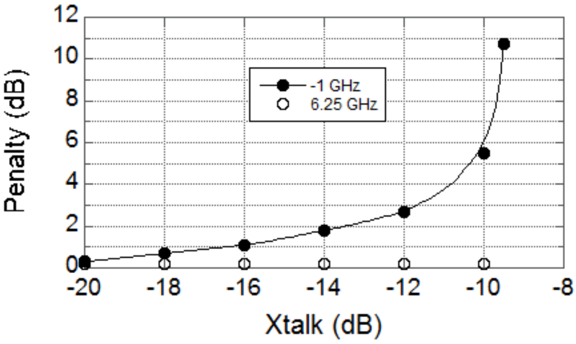

Fig. 8. Power penalty at BER $2{\cdot}10^{-3}$ vs. crosstalk level at 1 GHz signal-interferer detuning (LO wavelength reuse back-reflection) and at 6.25 GHz, as considered in this work.

Back-reflections were emulated by tuning the interferer to the frequency of the channel (in upstream or downstream) closest to the signal. The results are shown in Fig. 8 where the measured power penalty is plotted against the crosstalk level.. As can be seen, at 6.25 GHz_no penalty is induced by the interferer at all considered crosstalk levels.

We did not consider to reuse the LO as a source for upstream transmission, as proposed by various groups in order to simplify further the ONU architecture [9][10][11] for a number of reasons. In the first place, our PI-RX uses intradyne detection (LO detuning around −1 GHz) and simple ASK modulation. In these conditions reuse of the LO for upstream transmission could be quite problematic unless the reflectivity of the optical components in the ONU close to the LO is extremely low (< 50 dB). As shown in Fig. 8 (-1 GHz curve) LO reflected powers 15 dB below the signal could still be managed but larger reflections rapidly become deleterious due to the coherent nature of the crosstalk [25]. Therefore, suitable countermeasures should be taken to mitigate reflection impairments, such as inserting high-pass filters after the photodiodes on the three electrical arms to remove baseband interference [26].

Other solutions proposed in the literature make use of heterodyne detection and FEC in combination with spectral re-shaping, such as Nyquist filtering to avoid spectral superposition of the downstream and upstream signals [7][9][27]. In this way only one laser source (typically a tunable ECL) can be used as a LO and as a source for the downstream signal with highly efficient use of the spectrum, but the ONU complexity is greatly increased. Besides strong FEC and DSP, in general such schemes require high power lasers (for example 16 dBm in [9]). Our purpose instead is to maintain the ONU as simple as possible accepting the price of a reduced spectral efficiency

Moreover, techno-economical studies carried out in the framework of COCONUT activities show that using two separate DFB sources for the upstream signal and the LO is more cost effective than using a single laser [28]: the cost of a high power DFB laser plus additional optical components exceeds that of two common DFBs.

Then the effect of crosstalk from adjacent channels was investigated. In this case the interferer frequency was scanned across a 12 GHz range centered on the frequency of the signal under test and power penalty measurements were taken for various interferer power levels. The obtained results are shown in Fig. 9, where the power penalty with respect to FEC level, measured at 1 GHz frequency intervals from −6 GHz to +6 GHz signal-interferer detuning, are shown for interferer powers ranging from 20 dB to 0 dB below the signal level.

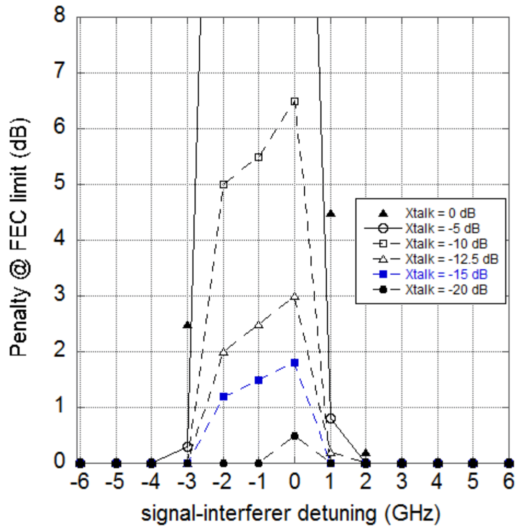

Fig. 9. Power penalty (FEC level) vs signal-interferer detuning for various crosstalk levels.

The penalty curve appears to be centered around the LO frequency (at about -1 GHz) and the worst situation is observed when the interferer frequency coincides with that of the signal. Due to the coherent nature of the crosstalk, the penalty grows dramatically with the crosstalk level [25]. Instead, no significant impairment is observed when the signal-interferer detuning is outside the −3 GHz ÷ +2 GHz detuning interval, for all considered crosstalk levels. This can be ascribed to the fact that for large detuning the interferer channel acts as additive noise, which is much less critical [25]. These results prove that the proposed PI-RX is fully compatible with UD-WDM PON systems with 6.25 GHz spacing. The use of tighter spacing is precluded by the intradyne operation of the receiver and by the use of simple ASK modulation with his low spectral efficiency [9].

Finally, the dynamic range of the system was measured to prove the suitability of the solution in a real PON environment. In an actual PON the ODN loss can largely vary among the different ONU's and the OLT receivers, therefore it is critical that the RX can work across a wide range of different received power levels. We thus measured the BER values as function of input power, thus simulating a variable ODN loss. Results are reported in Fig. 10. They show that (at FEC level) around 52 dB dynamic range is achieved. This value is by far higher than the expected variations in practical environments (between 15 and 23 dB in current standardized PON systems [29][30]) and opens to the possibility of implementing PON with much higher differential losses.

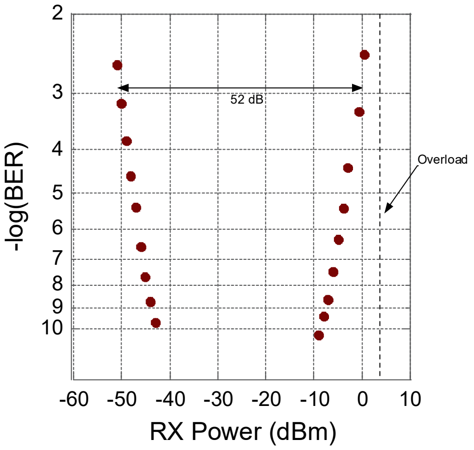

Fig. 10. Measured dynamic range (in back-to-back) of the proposed PI-RX.

IV. CONCLUSION

We have presented the first implementation of a real time 1.25 Gb/s ASK coherent PON system that takes advantage of a polarization independent receiver based on simple analogue processing, without the need of DSP (nor ADC), and on common DFB lasers. We obtained a very good sensitivity (around −51 dBm at FEC level) despite the limited complexity. The PI-RX has no apparent error floor down to BER=10^{-10} and shows no significant penalty with respect to what can be achieved by offline processing. Robustness of the PI-RX against back-reflections and crosstalk from adjacent channels has been investigated. At the present preliminary development stage, FEC coding is needed to enable some network features such as wavelength reuse of the Local Oscillator but full compatibility with UD-WDM-PON environment with channel spacing down to 5 GHz has been demonstrated. The measured dynamic range of the receiver is found to be 52 dB at BER=10^{-3} (35 dB at BER=10^{-9}), largely exceeding expected needs.

In addition, the coherent receiver is also compatible with a common Directly-Modulated Laser (DML) used at the transmitter, even in a 8×1.25 Gbit/s UD-WDM configuration as shown by us in [31].

A picture of the inside of the assembled prototype is shown in Fig. 11. As can be seen, this is a preliminary implementation made of discrete electronic and optical components. There is therefore room for a substantial footprint reduction, for example by mounting all Electronic ICs and optoelectronics components on a single printed circuit board (at the moment all have their individual board) and optimizing the arrangement of the discrete optical circuit. Work is in progress to improve the receiver performance in terms of crosstalk resilience and to further reduce its complexity. Moreover, preliminary tests indicate that the receiver can be scaled to higher bit rates (e.g. 2.5 Gb/s and 10 Gb/s), which we previously demonstrated by offline processing only [32]. Of course the price to be paid for using simpler analog receivers is the loss of the flexibility offered by DSP, However, thanks to the common availability of the IC's used for the analog processing and their affordable cost and the possibility to integrate on a photonic chip the optical front-end [22], these results can open the way to a completely new paradigm of coherent optical access networks.

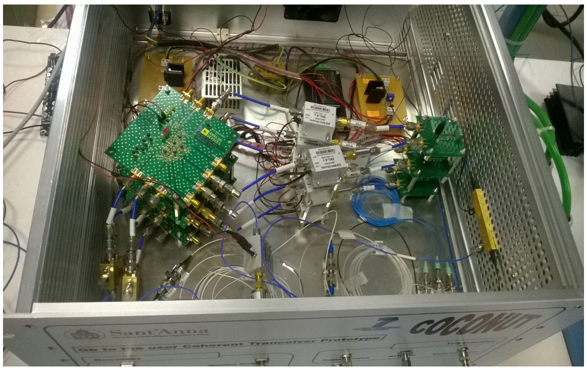

Fig. 11. Assembled prototype of the proposed PI-RX.

REFERENCES

[1] Special issue "5G wireless communication systems: prospects and challenges", *IEEE Communications Magazine*, Vol. 52, Issue 2, February 2014; "5G wireless communication systems: prospects and challenges: part 2", *IEEE Communications Magazine*, Vol. 52, Issue 5, May 2014

[2] P.Chanclou , A. Cui, F. Geilhardt, H. Nakamura and D. Nesset, "Network Operator Requirements for the Next Generation of Optical Access Networks," in *IEEE Network*, pp. 8-14, March/April 2011

[3] Ip, E., Lau, A. P. T., Barros, D. J., & Kahn, J. M. (2008). Coherent detection in optical fiber systems. Optics Express, 16(2), 753-791.

[4] H. Rohde, S. Smolorz, J. Sh. Wey and E. Gottwald., "Coherent optical access networks," *Proc. Opt. Fiber Comm. Conf.*, OFC 2011, paper OTuB1.

[5] "*Gigabit-Capable passive optical networks (GPON)*". ITU-T Rec. Series G.984, 2004

[6] Lavery, D., Maher, R., Millar, D., Thomsen, B. C., Bayvel, P., & Savory, S. (2012, March). Demonstration of 10~ Gbit/s colorless coherent PON incorporating tunable DS-DBR lasers and low-complexity parallel DSP. In Optical Fiber Communication Conference (paper. PDP5B-10). Optical Society of America.

[7] H. Rohde, E. Gottwald, A. Teixeira, J. D. reis, A. Shahpari, K. Pulverer and J.Sh. Wey, "Coherent Ultra Dense WDM Technology for Next Generation Optical Metro and Access Networks," IEEE Jour. of Lightwave Technology, vol. LT-32, no. 10, pp. 2041–2052, May 15, 2014

[8] Lavery, D., Maher, R., Millar, D. S., Thomsen, B. C., Bayvel, P., & Savory, S. J. (2013) "Digital coherent receivers for long-reach optical access networks" Lightwave Technology, Journal of, 31(4), 609-620.

[9] Reis, J., Shahpari, A., Ferreira, R., Ziaie, S., Neves, D., Lima, M., & Teixeira, A., Terabit+ (192× 10 Gb/s) Nyquist shaped UDWDM coherent PON with upstream and downstream over a 12.8 nm band. *IEEE Jour. of Lightwave Technology, Vol 32*, no. 4, pp, 729-735, 2004

[10] Shim, H. K., Kim, H., and Chung, Y. C., "Practical 12.5-Gb/s, 12.5-GHz spaced ultra-dense WDM PON", *Optics Express*, Vol. 22, no. 23, 29037-29047, 2014.

[11] S. Narikawa, H. Sanjoh, N. Sakurai, K. Kumozaki, and T. Imai, "Coherent WDM-PON using directly modulated local laser for simple heterodyne transceiver," in *Proc.of ECOC*, Sept. 2005, Paper We3.3.2.

[12] J. Prat, et al., "Towards ultra-dense wavelength-to-theuser: The approach of the COCONUT project," *Proc. Intern. Conf. on Transp. Opt. Networks*, ICTON 2013.

[13] M. Presi, et al. "All DFB-Based Coherent UDWDM PON With 6.25 GHz Spacing and a >40 dB Power Budget," *IEEE Photon. Techn. Lett.*, vol. 26, .no. 2, pp.107-110, .2014.

[14] E. Ciaramella "Polarization-Independent Receivers for low-cost Coherent OOK systems", *IEEE Photon. Techn.Lett.*, vol. 26, no. 6, pp.548-551, 2014.

[15] M. Presi, R. Corsini and E. Ciaramella, "Experimental demonstration of a novel polarization-independent coherent receiver for PONs," *Tech. Digest of Conference on Optical Fiber Communications, OFC 2014*, paper W4G.3, Optical Society of America, 2014

[16] M. S. Erkilinc, D. Lavery, R. Maher, M. Paskov, B. C. Thomsen, P. Bayvel, R. I. Killey1, S. J. Savory; "Polarization-Insensitive Single Balanced Photodiode Coherent Receiver for Passive Optical Networks", *proc. of ECOC 2015*, Valencia, paper Th.1.3.3

[17] Glance, B. 'Polarization independent coherent optical receivers', *IEEE Jour. Lightwave Technol.*, vol. LT-5, no. 2 ,pp. 274-276, Febr. 1987

[18] I. Cano, A. Lerin, V. Polo, J. Prat, "Directly Modulated DFB with Phase Diversity in Time Polarization Independent Intradyne Receiver for UDWDM-PON", proc. ECOC 2015, Valencia, paper Th.1.3.4

[19] E. Ciaramella, F. Bottoni, M. Rannello, M. Artiglia, M. Presi, "Coherent PON System with High-Sensitivity Polarization-Independent Receiver and no ADC/DSP"; proc. ECOC 2015, Valencia, paper Th.1.3.2

[20] M. Presi et al., "Low Cost 6.25 GHz UDWDM PON based on Directly Modulated DFBs", *Tech. Digest of Conference on Optical Fiber Communications, OFC 2015*, Los Angeles, CA, paper Th3I.1

[21] L. G. Kazovsky, "Phase- and Polarization-Diversity Coherent Optical Techniques," *IEEE Jour.Lightwave Technol*., vol. LT-7, no. 2, pp. 279–292, Febr. 1989

[22] C. Xie, "Colorless Coherent Receiver Using 3x3 Coupler Hybrids and Single-Ended Detection," *Optics Express*, vol. 20, pp. 1164–1171, 2012

[23] De Krom, Wilbert HC. "Sensitivity degradation of an optical {2× 2} and a {3× 3} phase diversity ASK receiver due to gain imbalance and nonideal phase relations of the optical hybrid." IEEE Jour. *Lightwave Technol., Vol.* 9, no 11, pp. 1593-1601, 1991.

[24] ITU-T Rec. G.975.1, *Forward error correction for high bit-rate DWDM submarine systems, (2004)*

[25] Goldstein, E. L., L. Eskildsen, and A. F. Elrefaie. "Performance implications of component crosstalk in transparent lightwave networks." *IEEE Photonics Technology Letters,* Vol. 6, no. 5, pp.657-660, 1994

[26] S.P Jung, Y. Takushima, K. Y. Cho, S. J. Park and Y. C. Chung, "Demonstration of RSOA-based WDM PON Employing Self-Homodyne Receiver with High Reflection Tolerance". Proc. of Optical Fiber Communication Conference (OFC), pp. JWA69, March 2009.

[27] D. Lavery, M. Paskov, S.J. Savory "Spectral Shaping for Mitigating Backreflections in a Bidirectional 10 Gbit/s Coherent WDM-PON," in Proc. of Optical Fiber Communication Conference (OFC), pp. OM2A6, March 2013.

[28] G. Vall-llosera, A, Rafel, N. Parkin M. Angelou, D. Klonidis, I. Cano, M. Presi, G. Papastergiou, I. Tomkos, J. Prat and Ciaramella, E.. COCONUT cost, power consumption and migration analysis: A route towards NG-PON3. In *17th International Conference on Transparent Optical Networks (ICTON),* pp. 1-4 (July 2015)

[29] ITU-T Rec. G.984.2 "*Gigabit-Capable passive optical networks (GPON): General Requirements*".

[30] ITU-T Rec. G.987.2, "10-*Gigabit-Capable passive optical networks (XG-PON: General Requirements* "

[31] M. Presi, R, Corsini, M. Artiglia and E. Ciaramella, "Ultra-Dense WDM-PON 6.25 GHz spaced 8×1 Gb/s based on a simplified coherent-detection scheme", *OSA Optics Express*, vol. 23, no. 17, pp. 22706-22713, 24 Aug. 2015

[32] M. Artiglia, R. Corsini, M. Presi, F. Bottoni, G.Cossu and E. Ciaramella, "Coherent systems for low-cost 10 Gb/s Optical Access Networks", *IEEE Jour. Lightwave Technol.*, Vol. 33, no. 15, pp. 3338-3344, Aug. 2015.