Research Article | Vol. 25, No. 15 | 24 Jul 2017 | OPTICS EXPRESS 17841
Optics EXPRESS

10 Gb/s long-reach PON system based on directly modulated transmitters and simple polarization independent coherent receiver

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Abstract: We demonstrate a coherent 10 Gb/s PON system solution exploiting a direct modulated laser (DML) transmitter to obtain long reach (>100 km). The system exploits a simplified coherent receiver. This receiver, which is similar to the scheme that we recently proposed, had to be adapted to obtain polarization-independent operation with a chirped signal from a DML and is still based on simple optical and electrical components. Thanks to the combined use of coherent-RX and DML, the system achieves a link budget of 43 dB for 105 km transmission distance with no need of dispersion compensation. This makes it a cost-effective, simple, and robust solution for satisfying the increasing capacity request of access networks.

OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications; (060.2380) Fiber optics sources and detectors.

References and links

1. D. Nesset, M. Scopes, R. Davey, D. Shea, P. Healey, A. Borghesani, D. Moodie, A. Poustie, and R. Wyatt, "Demonstration of 100km reach amplified PONs with upstream bit-rates of 2.5 Gbit/s and 10 Gbit/s," in *European Conference on Optical Communication 2004*, paper We2.6.3.
2. E. Wong, "Next-Generation Broadband Access Networks and Technologies," J. Lightwave Technol. **30**(4), 597–608 (2012).
3. H. Song, B. W. Kim, and B. Mukherjee, "Longreach optical access networks: A survey of research challenges, demonstrations, and bandwidth assignment mechanisms," IEEE Comm. Surv. and Tutor. **12**(1), 112–123 (2010).
4. E. Ip, A. P. T. Lau, D. J. Barros, and J. M. Kahn, "Coherent detection in optical fiber systems," Opt. Express **16**(2), 753–791 (2008).
5. D. Lavery, M. Ionescu, S. Makovejs, E. Torrengo, and S. J. Savory, "A long-reach ultra-dense 10 Gbit/s WDM-PON using a digital coherent receiver," Opt. Express **18**(25), 25855–25860 (2010).
6. A. Shapari, R. Ferreira, R. Luis, Z. Vujicic, F. Guiomar, J. Reis and A. Texeira, "Coherent Access: a Review," accepted for publication on J. Lightwave Technol.
7. J. Prat, M. Angelou, C. Kazmierski, R. Pous, M. Presi, A. Rafel, G. Vall-Llosera, I. Tomkos, and E. Ciaramella, "Towards ultradense wavelength-to-the-user: The approach of the COCONUT project," in *15th International Conference on Transparent Optical Networks (ICTON) 2013*, pp. 14.
8. J. Zhou, F. Xu, E. Sun, T. Zhang, Z. Zhang, M. Guo, X. Tang, Z. Wang, and Y. Qiao, "Coherent Optical Interleaved SC-FDM Uplink Scheme for Long-Reach Passive Optical Network," IEEE Photonics J. **8**(2), 7902208 (2016).
9. Y. Li, Z. Deng, R. Hu, C. Li, W. Li, Z. Yuan, and S. Yu, "Low-cost Coherent UDWDM-PON by Hybrid DBPSK-ASK-2 Modulation," Opt. Commun. **370**, 222–225 (2016).
10. M. Luo, R. Hu, W. Li, Q. Yang, and S. Yu, "Cost-effective coherent ONU transceiver based on single directly modulated laser," Opt. Express **24**(12), 12879–12885 (2016).
11. I. N. Cano, J. Prat, J. Tabares, J. C. Velasquez, S. Ghasemi, V. Polo, G. Y. Chu, M. Presi, E. Ciaramella, M. Rannello, F. Bottoni, M. Artiglia, G. Cossu, R. Pous, G. Azcarate, C. Vila, H. Debregeas, G. Vall-Llosera, and A. Rafel, "Field-Trial of Low-Cost Coherent UDWDM-PON with Real-Time Processing, λ-Monitoring and EPON Coexistence," in *European Conference Optical Communication (ECOC) 2016*, paper M.1 E.5.
12. E. Ciaramella, "Polarization-Independent Receivers for low-cost Coherent OOK systems," IEEE Photonics Technol. Lett. **26**(6), 548–551 (2014).
13. M. Artiglia, R. Corsini, M. Presi, F. Bottoni, G. Cossu, and E. Ciaramella, "Coherent System for Low-Cost 10 Gb/s Optical Access Network," J. Lightwave Technol. **33**(15), 3338–3344 (2015).
14. Y. Matsui, D. Mahgerefteh, X. Zheng, C. Liao, Z. F. Fan, K. McCallion, and P. Tayebati, "Chirp-Managed Directly Modulated Laser (CML)," IEEE Photonics Technol. Lett. **18**(2), 385–387 (2006).
15. R. Corsini, M. Presi, M. Artiglia, and E. Ciaramella, "10 Gb/s Long-Reach PON System with Low-Complexity Dispersion-Managed Coherent receiver," IEEE Photonics J. **7**(5), 7103008 (2015).

#290275 https://doi.org/10.1364/OE.25.017841
Journal © 2017 Received 10 Mar 2017; revised 17 May 2017; accepted 18 May 2017; published 18 Jul 2017

16. D. P. Shea and J. E. Mitchell, “10 Gbit/s, 1024 way Split, 100km Long Reach Optical Access Networks,” J. Lightwave Technol. **26**(3), 685–693 (2007).

1. Introduction

Long-Reach Passive Optical Network (LR-PON) is an interesting solution of access architecture [1], able to address the increasing bandwidth request expected in the following years [2]. It increases network reach and reduces the number of central offices and active cabinets while serving a large number of costumers. The two main limiting factors in LR-PON are receiver sensitivity and chromatic dispersion, which is the strongest at 10 Gb/s or higher bit rates; both can potentially impose serious limitations to the maximum reach [3]. Recently, coherent detection, which is consolidated in core and metro networks [4], was proposed also for the access network, also in long-reach WDM-PON scenarios [5], thanks to the benefits it could provide in terms of sensitivity, frequency selectivity and spectral efficiency [6]. Since the requirements of the access scenario in terms of cost, simplicity and robustness [7] are much different, simplified solutions for coherent access, leveraging on new multiplexing schemes [8], or modulation formats [9], or components re-use [10] were proposed. However, in order to effectively tackle the cost constraint, the design of coherent access systems should go far beyond the simple re-scaling of the core-metro solutions to lower bit-rates: in the framework of the COCONUT EU project several solutions of low-cost coherent transceivers for WDM-PONs were proposed, avoiding the use of costly components like 90 degrees hybrids or massive DSP [11]. In particular, in [12] a novel polarization-independent (PI) scheme was introduced for intensity-modulated signals, which was later demonstrated up to 10 Gb/s [13]. PI property, based on spectral filtering effects, was demonstrated only using external modulation, which is more expensive than direct modulated lasers (DMLs) and severely limits the long-reach, due to the chromatic dispersion.

A cost-effective way to overcome dispersion limitations might be to use DML transmitters, that allow long distance reach, thanks to careful exploitation of their adiabatic chirp [14]. In [15], a simple 10 Gb/s LR-PON has been demonstrated by using a transmission technique inspired by chirp managed lasers (CML). This result was obtained in single-polarization operation, with the State of Polarization (SoP) between signal and local oscillator (LO) manually aligned. Extension to PI configuration was not possible at that time, due to the combined effects of chirp and filtering at the receiver.

Here we experimentally demonstrate, for the first time, the extension of PI-Rx proposed in [12] to the use with a DML signal, whose spectral properties are much different from usual intensity-modulated signal produced by external modulation. The extension is obtained by revising the RX architecture, including a novel filtering stage. This allows to obtain a coherent, low-cost, polarization independent detection, that, together with DMLs, features long distance reach (> 100 km) without dispersion compensation. Given the modifications applied to the PI-RX, we also experimentally investigate the system tolerance to the presence of a side-channel, and measure its impact on the performance.

2. Working principle and experimental setup

The receiver scheme is presented in Fig. 1(a), where we also show the experimental setup. As transmitters, we use commercial off-the-shelf TOSA packaged Distributed Feed-Back (DFB) lasers, suitable for 2.5 Gb/s nominal operation. Their center wavelength is controlled by acting on the temperature and the bias current for coarse and fine tuning, respectively. At the Optical Line Terminal (OLT) side, a DFB laser (DFB-1) acts as channel under test and is directly modulated by a NRZ PRBS at 10 Gb/s. The modulation depth of the laser is 1.1 V, so that an adiabatic chirp between the '1' and '0' power levels equal to half of the bit-rate (around 5 GHz) (see Fig. 1(b)): in this case, a phase correlation between the '1' bits of the signal is introduced, so that destructive interference occurs between '1' pulses separated by a '0' bit. This can effectively compensate for the spreading and overlapping of the pulses due to

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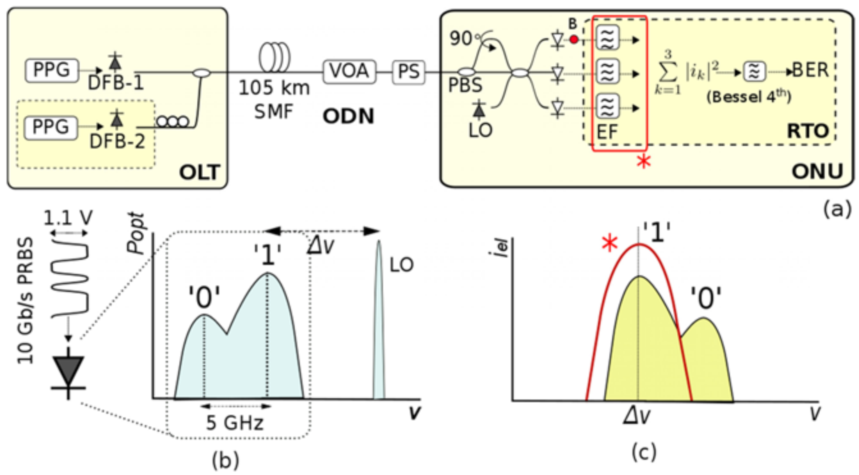

Fig. 1. (a) Experimental Setup: DFB: Distributed Feedback Laser; PPG: pattern generator; SMF: Single Mode Fiber; VOA: Variable Optical Attenuator; PS: polarization scrambler; OLT: Optical Line Terminal; ONU: Optical Network Unit; PBS: Polarization Beam Splitter; LO: Local Oscillator; EF: Electrical Filter; RTO: Real time oscilloscope; (b) generation of chirp managed optical signal and sketch of the optical spectrum. Δν: Frequency detuning between channel and LO; (c) sketch of the spectrum of one electrical output at point B in (a) and profile of the pass-band filter (red line)

chromatic dispersion effect [14]. A second DFB (DFB-2) acts as interfering channel (or channel 2) and is modulated by a second, uncorrelated PRBS. Its SoP is controlled by a manual polarization controller (PC), to align it to the SoP of the first signal, and maximize the interference effect. The output power is around + 8 dBm.

The two signals are sent in the Optical Distribution Network (ODN), which is made up by a cascaded combination of G.652 fiber spools (D = 16 ps/nm/km), for a total transmission distance up to 105 km, and an optical VOA that emulates the network splitting losses; a Polarization Scrambler (PS) randomly varies the SoP of the signal uniformly all-over the Poincaré sphere, with a scrambling frequency of 100 Hz.

At the Optical Network Unit (ONU), the signal enters the RX, which resembles the PI scheme of [12], but was suitably modified in order to work with a CML signal. The two orthogonal components of the received signal are separated by a PBS, and then aligned to two inputs of a symmetric 3x3 coupler. Another DFB is used as a LO (with no special phase/frequency control of the LO), with a frequency detuning of Δν from the mean frequency of the marks of the signal, and enters the third input of the coupler. The lightwaves from the three outputs of the coupler are detected by three 15 GHz PIN photodiodes with integrated trans-impedance amplifiers (TIAs). Figure 1(c) shows a sketch of the electrical spectrum of one of the detected photocurrents, with '1' lobe centered at the detuning Δν. A real-time oscilloscope (RTO, 13 GHz analogue bandwidth, 20 GSa/s) processes the three digitized PD currents for the envelope detection.

It has to be stressed that the analog processing used in [12] is suited for pure ASK signal, and here would not give a useful signal because of the spectral features of the CML signal. Therefore, we modified the electrical processing of [12] including, in first place, a band-pass filtering operation (Gaussian filter, 3 dB BW of 3 GHz, center frequency Δν) realized in a customized routine. The filters, centered around the '1' lobe of the spectrum, by partially removing the '0' lobe realize an FM-AM conversion that increases the extinction ratio (Fig. 1(c)). This operation is equivalent to the optical filtering realized in chirp-managed transmissions either right before the receiver [16], or transmitter [14]: here the use of coherent detection allows to move it into the electrical domain, where filters can be realized in an easier and cheaper way with a resolution bandwidth much higher than the optical ones. The

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output resembles a CML signal filtered in the optical domain, which is a good approximation of a ASK signal with a slow spurious phase modulation *Φ(t)*. We note that a different electrical filtering operation was also present in [15], where single-polarization operation allowed operating in homodyne, and therefore used a low-pass electrical filter. Since PI operation requires intradyne [12], the filter here must be suitably modified and changed into a band-pass with Δν central frequency. For our signal, PI demodulation can be then obtained similarly as for chirp-free ASK signal [12]. Squaring each filtered photocurrent and summing them together, gives the following output:

$$S(t) = \frac{2}{3} R^2 r(t)^2 E_{LO}{}^2 \left[1 - \sin\left(2\varphi\right) \sin\left(\frac{\pi}{6} - 4\pi\Delta\nu t - \psi - 2\Phi\left(t\right) \right) \right] \tag{1}$$

where R is the photodiodes responsivity, $E_{LO}{}^2$ is the local oscillator power, $r(t)$ is the modulating signal, φ and ψ correspond to the signal SoP . $S(t)$ has two main contributions: the first in baseband, which is the correct demodulated signal, and the second centered at around $2\Delta\nu$, which can give dramatic impairments [12]; here only the second depends on the signal SoP, but the usual low-pass Bessel filter (3 dB bandwidth of 7.5 GHz) strongly reduces this contribution, obtaining PI operation [12]. In a home-made routine in the RTO, we also evaluate the BER value, by directly comparing bit-by-bit the transmitted and the received sequences (offline processing limits the length of the transmitted sequence to 2^7-1 bits).

3. Experimental results

In first place, PI functionality of the RX was verified in back to back (B2B), single channel, BER measurements. The results are reported in Fig. 2(a) where BER curves taken in different conditions of fixed signal SoP (with manual alignement with LO) are compared to the one measured with the PI configuration and the PS active. At FEC level (BER = 2×10^{-3}), the sensitivity value is –36.5 dBm, and there is no visible penalty between single and random SoP conditions.

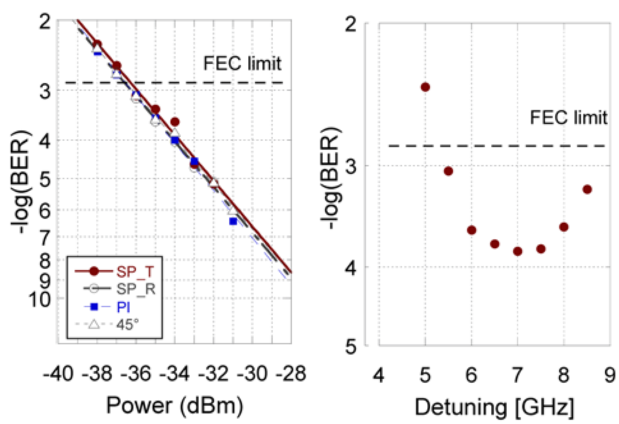

Fig. 2. Single channel B2B results. (a) BER vs. received power for horizontal fixed linear polarizations: horizontal (red dots), vertical (white dots), 45 degrees (white triangles) and in PI configuration (blue squares). (b) BER vs. detuning, for –34 dBm received power.

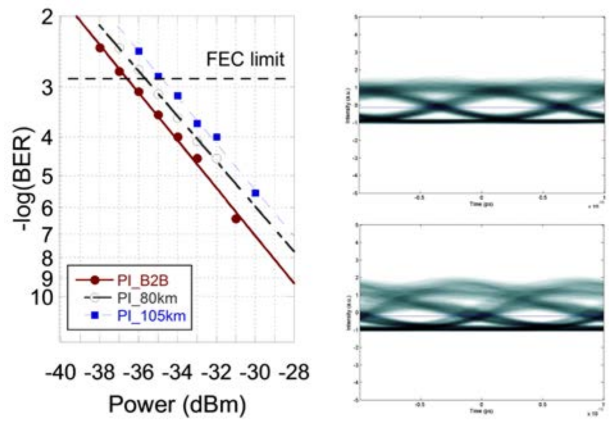

Fig. 3. Single channel results. (a): BER vs. received power in back to back (red dots), after 80 km (white dots), and 105 km (blue squares) transmission. (b): eye diagrams at −30 dBm received power in back to back (upper) and 105 km transmission (lower).

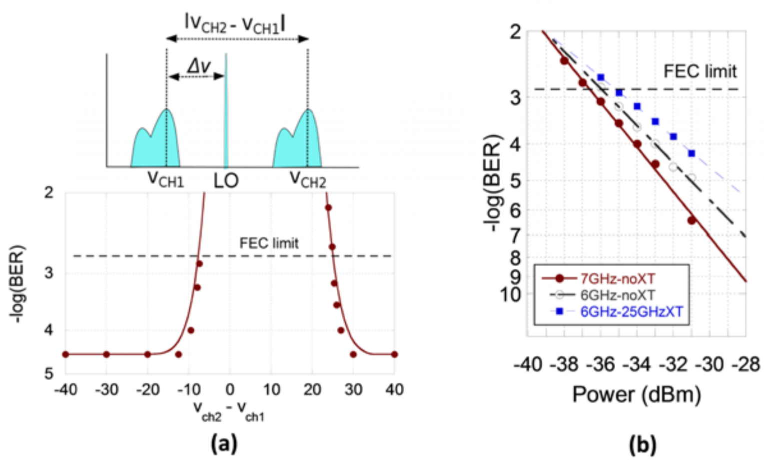

Fig. 4. (a) BER value measured on channel 1 for a received power of −33 dBm and a detuning with the LO Δν = 7 GHz, as a function of the difference between center frequencies of channel 1 and 2 (bottom). Explicative sketch of the optical signals for dual channel measurement (top) (b) BER vs. Received Power for a ν_2-ν_1 = 25 GHz and Δν = 6 GHz (blue squared line), compared with single channel BER with Δν = 6 GHz (white dotted line), and single channel BER with Δν = 7 GHz (red dotted line)

This result is consistent with those of [15], once the insertion loss of the PBS (≈1.5 dB) is taken into account. The optimal detuning between the signal carrier and LO was determined by minimizing the BER at a given power (Fig. 2(b)). Despite this value was predicted in [12] to be around 85-90% of the bit-rate (i.e. 8.5-9 GHz), experimentally we found it slightly lower (7 GHz). This could be ascribed to the limited frequency response of the oscilloscope in use, that affected the behavior of the RX at higher frequencies..

Single channel performance of the system under propagation was measured with different propagation distances, and compared to B2B. Results are reported in Fig. 3, where BER curves and eye diagrams obtained with 105 km of SMF transmission are compared with B2B. As can be noticed, CMLs allows transmission of the signal over 80 and 105 km with a penalty of 0.8 and 1.5 dB, respectively. These two values yield a link budget of 43.8 dB for 80 km reach and around 43 dB for 105 km. Considering a fiber loss of 0.22 dB/km, and a system tolerance of around 2 dB, these values are compatible with a PON serving up to 64 users on a

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maximum reach of 105 km, or up to 256 users over a maximum reach of 80 km. Sensitivity values are comparable with [16], where low cost transmitter based on DMLs was also exploited, but distance reach was increased by optical amplifiers over the line, and dispersion penalty was reduced by a narrow optical filtering before the detection of the signal (2 nm filter bandwidth), allowing a resolution bandwidth not lower than 250 GHz.

We then investigated the system performance in presence of an interfering WDM channel. Figure 4(a) shows the BER value obtained with a received power of –33 dBm, as a function of the frequency difference ν_{ch1}-ν_{ch2}. It is clear that the system is not affected significantly by the presence of the second channel, for spacing as low as 30 GHz; thus, for example, channel spacing down to 50 GHz can be supported without penalty. A penalty shows up as the spectrum of the interfering channel stands on the same side of the LO with respect to the test channel (as sketched in Fig. 4(a)). This is due to the image frequency effect appearing when the distance between interfering channel and LO is close enough to push the spectrum of the first inside the electrical bandwidth of the receiver: that makes channel spacing of 25 GHz no longer suitable.

However, further investigation was made upon the condition of 25 GHz spacing, in order to limit the power penalty properly optimizing the system settings. In particular, measurements were carried out reducing the LO detuning to 6 GHz. This value, even if not the optimal one for single channel operation (Fig. 2(b)), results to be the best trade-off between the best single-channel performance and the need to suppress the electrical crosstalk of the adjacent channel. Figure 4(b) compares BER curves obtained in single channel operation with 7 GHz LO detuning, and with 6 GHz LO detuning, with and without the interfering channel. At FEC limit, overall penalty is below 1 dB, and the measured sensitivity is –35.5 dBm.

4. Conclusions

We demonstrated a 10 Gb/s LR-PON, featuring a simple DML transmitter and a coherent PI-RX, based on simple low-cost optical and electrical components, with no need of DSP for polarization control or chromatic dispersion compensation. The PI-RX is properly modified from a known scheme, but requires optimized electrical filters to operate with a DML signal; this allows obtaining for the first time both coherent PI-operation and chirp management. Pre-FEC sensitivity of –36.5 dBm in B2B, with a transmission penalty <1 dB over 80 km and 1.5 dB over 105 km of SMF. Power budget is of 43.8 dB with an 80 km reach and 43 dB with 105 km reach, allowing the PON to serve up to 256 and 64 users, respectively. We also proved that a Nx10 Gb/s system allows for channel spacing of 50 GHz with no penalty, and of 25 GHz with a penalty <1dB. Extension of the system to operate at higher line rates (25 Gb/s or 40 Gb/s) is currently under investigation.