4×10 Gb/s Coherent WDM-PON System over 110 km of Single Mode Fibre and with 55 dB ODN Power Budget

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ABSTRACT
We experimentally show that, using simplified coherent detection and directly modulated DFB lasers, a 40 Gb/s (4×10 Gbit/s) WDM-PON system can be realized, providing a very high power budget (55 dB) and 110 km reach. This enhances currently considered NG-PON2 solutions, both in terms of reach and acceptable loss.
Keywords: optical communications, coherent detection, filterless access networks, long-reach passive optical networks.

1. INTRODUCTION

To face the challenges raised by the convergence of wired and wireless networks onto a single access infrastructure, as foreseen for the future 5G networks, Wavelength Division Multiplexing (WDM) has been recently introduced as an additional resource in the latest standard on Passive Optical Networks (PONs), known as NG-PON2 [1]. NG-PON2 is a hybrid PON were the synergy of Time Division Multiplexing and WDM is exploited (TWDM-PON) stacking up to 8 pairs of wavelengths to achieve an aggregate capacity of up to 80 Gb/s downstream and 80 Gb/s upstream. Reach, up to 40 km, and ODN (Optical Distribution Network) power budgets, up to 35 dB, remain unchanged with respect to previous standards.

However, the need to increase the PON optical power budget at reduced costs and ensuring backward system compatibility is becoming compelling. Higher optical power budgets can support a higher number of ONUs per ODN and will allow to deploy PON of longer reach favouring a higher degree of infrastructure sharing and of network consolidation. Network consolidation is already addressed within PON ITU-T standards through the introduction of Reach-Extenders (ITU-T G.984.6, G.987.4), i.e. devices able to guarantee PON operation over distance up to 60 km. However, as pointed out by the recently expired EU FP7 Project DISCUS [2], much longer reach (up to 100 km) is required to better exploit network consolidation advantages (Long Reach PON, LR-PON). An attractive solution to achieve very high loss budgets is introducing coherent detection and digital signal processing (DSP) in the access segment [3][4]. Yet, the paradigm of current coherent receiver technology used in core and metro networks, based on high-speed A/D converters, advanced DSP and expensive local oscillator (LO) lasers, cannot be applied to access applications where the dominant criterion is cost-effectiveness [5].

Recently, within the COCONUT EU FP7 project [6], we demonstrated a cost-effective 10 Gb/s LR-PON based on a Directly Modulated Laser (DML), where a low-complexity coherent receiver with simple post-detection filtering [7] produces an effect similar to chirp management [8] so as to compensate for fibre dispersion. In this paper, we build on the approach of [7] and extend it to a WDM scenario (4λ's). We chose a 4×10 Gb/s configuration and demonstrate 40 Gb/s downstream (DS) aggregated bit-rate over an optical distribution network (ODN) consisting of 110 km of standard Single Mode Fibre (SMF). Power budgets up to 55 dB are obtained, capable of supporting fibre loss plus a potential total split ratio up to 1:256. The proposed system can thus be seen as a DS extension of the TWDM-PON concept since it can support both higher sensitivity at the receiver and higher launch power thanks to the use of DMLs.

2. EXPERIMENTAL SET-UP

The proposed WDM-PON architecture is shown in Fig. 1. It emulates the downstream path of a long-reach, high ODN loss (>50 dB) PON. At the OLT side, we used four 10 Gbit/s directly modulated DFB lasers (DMLs) as downstream transmitters. Laser emission frequencies were 100 GHz spaced on the ITU-T DWDM grid, in a range from 193.4 to 193.7 THz (1547.7 ÷ 1551.1 nm). Typical laser line-width was around 10 MHz. Their output signals were sent to the four corresponding ports of a 100GHz DWDM arrayed waveguide grating (AWG) to achieve the 40 Gb/s aggregate rate.

In each transmitter unit, the DMLs were driven by 10 Gb/s pseudorandom bit sequence (PRBS) data with a word length of 2^7-1 generated by a two channel PPG. Two independent PRBSs were used together with the negated ones. Neighbour channels were also uncorrelated by adding patch-cords of different lengths before the AWG. On each of the four arms before the AWG we placed polarization controllers (PC) to adjust the mutual polarizations of the four channels. After multiplexing, the signals were amplified up to a total power of 23 dBm by an erbium-doped fibre amplifier (EDFA) booster. DMLs, AWG and EDFA made up the OLT side of the WDM-PON. The ODN consisted of spools of SMF (G.652, D = 16 ps/nm/km; α = 0.2 dB/km) of various lengths combined to obtain a fibre line of 110 km, and a Variable Optical Attenuator (VOA) simulating the loss of passive splitters.

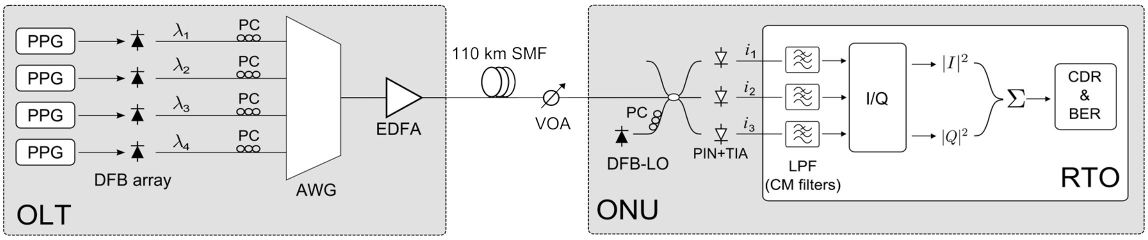

Figure 1. Schematic of the 4x10Gb/s WDM-PON system.

At the ONU side, a phase-diversity coherent receiver based on a 3x3 symmetrical fused-fibre optical coupler (120° hybrid) was used [9]. In this receiver, no tuneable optical filter was required neither any special source as a LO: a set of three common DFBs (DFB-LO, average linewidth ~10 MHz) were used as LOs to select the four downstream channels. The DFB-LOs were operated without any frequency control system (only controlled by usual thermal and intensity controllers). We note that by using a narrow band tuneable laser diode, such as a 1550 nm Distributed Bragg Reflector Laser, all channels could be selected using a single LO source. The signal and the respective LO were mixed by the 3×3 symmetrical coupler and then received by three photodiodes (PD) each having a responsivity of 0.6 A/W, 15 GHz bandwidth and an integrated trans-impedance amplifier. In this specific implementation, the polarization states of the LO and the signal were mutually aligned by a manual polarization controller (PC). The three output photocurrents were then acquired by a real-time oscilloscope (RTO, 13 GHz analogue bandwidth, 40 GSa/s) and processed off-line as described below. In the usual implementation of the receiver, ASK demodulation simply requires squaring and summing the three photocurrents [9][10]. Here, however, a key element, is added, which is emulating in the electrical domain the well-known CM approach. In the CM approach [8], an OSR (Optical Spectrum Reshaper) is required, which is usually realized by an optical filter embedded in the transmitter. Here a similar CM effect is very simply obtained by matching the modulation depth of the DMLs (yielding about 5 GHz dynamic chirp) with electrical low-pass filters of suitable slope in each of the three photodiode current paths (see LPFs in Fig. 1) [7]. In this proof-of-concept experiment, the EFs were implemented by using a built-in digital low pass filter function (3 GHz bandwidth, Gaussian shape, and linear phase) in the RTO before envelope reconstruction; in a real-time implementation of the RX, they could be simply realized by analogue electronic filters. Similarly to the CM case, the signal-LO detuning was set so that the signal spectrum fell on the right EF slope. The ASK signal envelope was finally recovered by combining the three filtered photocurrents so as to obtain the I and Q components of the signal; I and Q are then squared and finally summed up as shown in Fig. 1. The bit error ratio (BER) was also computed off-line comparing bit-by-bit the received sequence against the transmitted sequence, by means of a software routine run by the RTO processor. The use of short PRBS was dictated by memory storage limits of the RTO when performing off-line processing.

3. TRANSMISSION EXPERIMENT: RESULTS AND DISCUSSION

To characterise the system performance, BER versus received power measurements were performed for various values of channel powers at the fibre input, ranging from 10 dBm/ch to 17 dBm/channel. Figure 2a reports the optical spectra taken at the input of the link at 17 dBm/ch input power (dashed red curve) and the corresponding output (continuous blue curve). These data were taken for maximal polarization alignment among the WDM signals. Four Wave Mixing (FWM) products do actually appear, but they are 40 dB below the channel level: such low FWM is known to be very well tolerated. This is apparent in Fig. 2b, where the four eye diagrams taken at the receiver end in the same conditions are shown. All of them are well open and without significant distortions, either due to dispersion or to FWM. We outline that using chirped DMLs allowed us to reach the above high launch power levels without adopting countermeasures for suppressing Stimulated Brillouin Scattering (SBS). This is a intrinsic key strength of our system, enabling to enhance the overall power budget.

The measured BER curves are reported in Fig. 3. The curves in back-to-back for all channels are shown in Fig. 3a, where a remarkable maximum pre-FEC sensitivity of −38 dBm can be observed (FEC level 1.4×10^{-3}, light FEC, 7% overhead). On the other hand, Fig. 3b reports the curves taken on the four WDM channels after propagation with the maximum input power (17 dBm/channel, limited by the used EDFA). As we see, a pre-FEC penalty of about 1 dB is observed after 110 km propagation at such high launch powers. Similar curves were taken also for lower launch power values. An example is given in Fig. 3c where the BER curves for channel 3 (identified by the arrow in Fig. 2a) in b2b, with 11 dBm/ch (total power 17 dBm) and 17 dBm/ch (total power 23 dBm) after propagation are shown. As can be seen, most of the penalty can be ascribed to fibre dispersion rather than to fibre non-linearity. The robustness of the system to SBS can be ascribed to the fact that direct modulation on the lasers effectively suppresses the optical carrier, thus keeping the system below the SBS threshold.

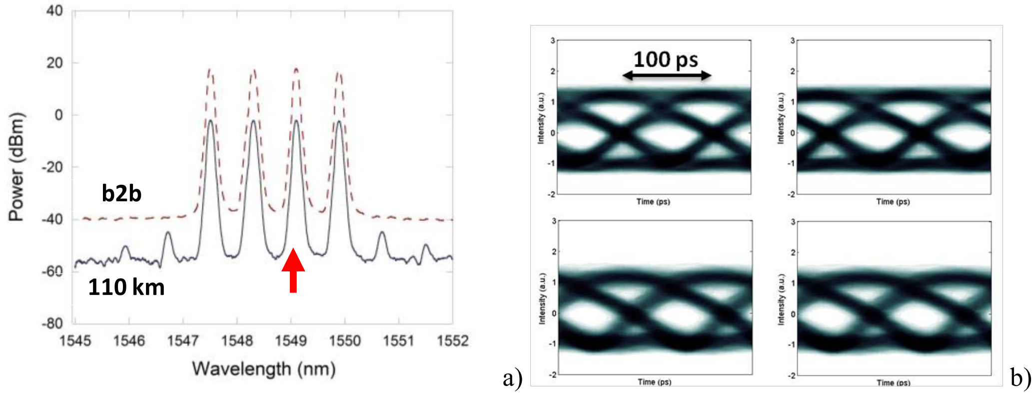

Figure 2: a) Optical Spectra before and after propagation; b) channel eye diagrams after propagation.

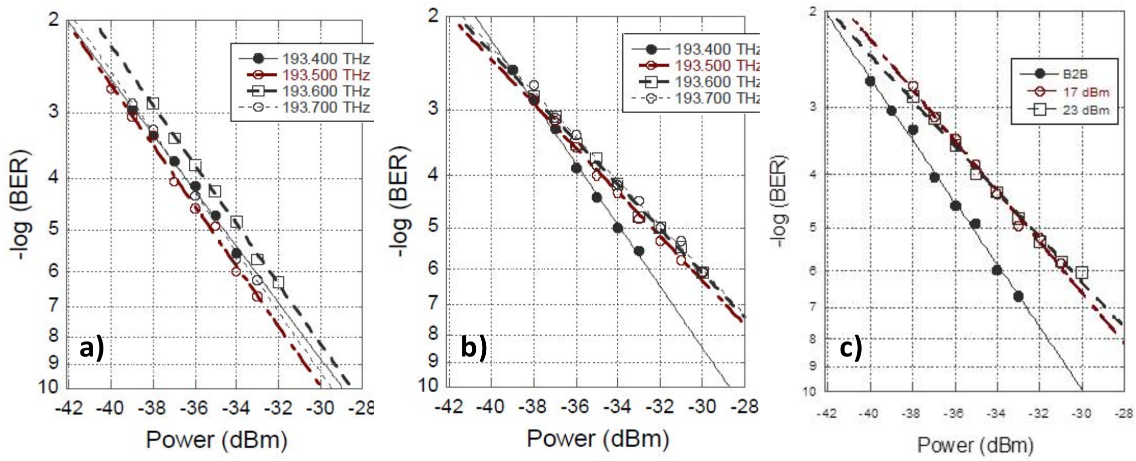

Figure 3. BER curves for: (a) all WDM channels back-to-back; (b) all WDM channels after 110 km propagation with 17 dBm launch power per channel; (c) channel 3 for different launch powers.

On the basis of the results sketched in Fig. 3 we could draw the main result of this paper, i.e., the average ODN loss that can be supported by each channel as a function of channel launch power. The resulting plot is shown in Fig 4. As we see, even reducing the power/channel at around 11 dBm, the system could still support almost 50 dB ODN loss, while up to 55 dB ODN loss can be achieved by increasing the channel launch power. A power budget of 55 dB would allow a splitting ratio of 1:256 after 110 km of SMF fibre (25 dB loss).

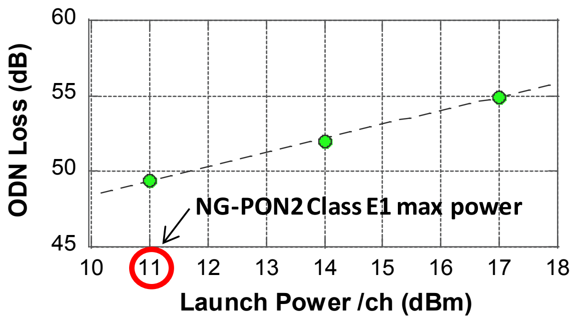

Figure 4. Maximum supported ODN loss as a function of input power/channel.

We note that our proof-of-concept experiment is performed in the C-band, whereas the standardised downstream frequencies for NG-PON2 sit in the 187.8 ÷ 187.1 THz band (1596 ÷ 1603 nm) thus requiring an L-Band EDFA booster. A concern that raises when using high power channels is related to the Raman depletion caused on coexisting channels at shorter wavelengths, such as the NG-PON2 upstream in this case, for which various options are proposed in the range from 1524 nm to 1544 nm. Using 60 nm average spacing among US and DS channels, we estimated that the Raman depletion penalty on US channel can be as high as 3 dB for 23 dBm DS total launch power and 110 km propagation, according to model described in [11]. Moreover, in order to use such high powers (> 21 dBm) into an installed plant, the WDM-PON system should feature an automatic laser shutdown mechanism, to avoid the risk of eye-damage to repair workers in case of fibre fault [12]. Nevertheless, using 11 dBm/ch can be viable: in that case, automatic shutdown is not required and Raman penalty on US channels goes down to around 0.7 dB. In this situation, our proposed WDM PON system can still support 50 dB of ODN loss, with a 10 dB advantage in ONU sensitivity with respect to the TWDM-PON (the maximum power for class E2 is 11 dBm as shown in Fig. 4) [1]. Considering 25 dB of fibre loss, about 25 dB of loss budget still remain available for splitting loss, corresponding to a realistic 1:128 splitting ratio.

4. CONCLUSIONS

In this work we demonstrated the feasibility of a WDM-PON system solution delivering 4×10 Gbit/s downstream capacity over a filterless, splitter-based ODN. The system combines simplified coherent detection at the receiver side (with common DFBs as LOs) and simple Directly Modulated Lasers at the transmitter side. Up to 55 dB ODN loss and a maximum span of 110 km are supported using an EDFA booster at the OLT. Dispersion compensation is not needed, although using DMLs. The measured pre-FEC power penalty after 110 km transmission is as low as 1 dB even at 17 dBm/ch. At power levels comparable to those used for TWDM (9 ÷ 11 dBm/ch) the loss budget is still as high as 50 dB, allowing for long reach operation with a 1:128 splitting ratio. Finally, we note that signal demodulation at the receiver can be performed in principle by simple analogue electrical processing and that the optical front end is clearly suitable for photonic integration. These features help to keep implementation costs low and can open the way to the implementation of future (T)WDM-PON solutions where higher performance is achieved in a cost-effective way.

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