Quaternary TDM-PAM as upgrade path of access PON beyond 10Gb/s

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Abstract: A 20 Gb/s quaternary TDM-PAM passive optical network with chirped and non-linear optical transmitters is experimentally demonstrated. The migration from legacy TDM-PONs and the implications of using available 10 Gb/s components are analyzed. We show that a loss budget of 27.3 dB is compatible together with a packet power ratio of 10 dB between loud and soft optical network units.

OCIS codes: (060.2360) Fiber optics links and subsystems; (250.4110) Modulators.

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1. Introduction

The success of time division multiplexing (TDM) in optical access relies on two cornerstones: its simplicity and the maturity of the utilized electro-optical devices. The photonic integration of laser diodes with external modulators provides a cost-effective user equipment without the need for cooling or wavelength stability. In contrast to wavelength division multiplexing (WDM), TDM has therefore reached a high market penetration through the Ethernet- and

#177198 - $15.00 USD Received 1 Oct 2012; revised 17 Nov 2012; accepted 19 Nov 2012; published 28 Nov 2012

Gigabit Passive Optical Network (E/GPON) standards and is currently deployed as 10 Gb/s solution through 10G-EPON and XGPON [1]. On top of this, TDM is also considered for NG-PON2 and has widely influenced recent research work, especially in reach-extended hybrid WDM/TDM PONs [2].

Still, the high peak data rate required to deliver an averaged low sustainable data rate questions the feasibility of TDM for high bit-rate PONs. A migration beyond 10 Gb/s to support business-class Fiber-To-The-Home or other bandwidth demanding services is primarily limited by the electrical bandwidth of the driving circuitry in the transmitter and the receiving subsystems. To alleviate this roadblock, a TWDM scheme has been proposed by different players in the field, using wavelength stacking and coarse WDM to provide 4 × 10 Gb/s per optical network unit (ONU) [3]. However, as bandwidth demand continues to scale up, this technique can obviously provide just an intermediate solution which also 4-folds the optical hardware at the communication terminal. Multi-level modulation needs to be taken into consideration as a new multiplexing dimension to effectively support a high network capacity without increasing the electrical bandwidth requirements of the applied components and without employing array transceivers. Though orthogonal frequency division multiplexing provides an elegant solution for advanced modulation [4], it requires heavy signal processing and is therefore not the first choice for short-term deployment. On the other hand, simpler formats such as duobinary or quaternary pulse amplitude modulation (4-PAM) can pave the way for a further upgrade of the data rate. In this work, we present 4-PAM transmission at 20 Gb/s in a TDM-PON, exploiting a low-drive chirped transmitter and a 10Gbit/s burst-mode trans-impedance amplifier. A packet power ratio of 10 dB between loud and soft packets is supported at a loss budget of 27.3 dB.

2. High bit-rate TDM-PON with low drive 4-PAM

Transmission of 20 Gb/s quaternary TDM-PAM was experimentally validated in the PON shown in Fig. 1. Two ONUs were used to emulate a scenario where a loud and soft transmitter are presented. Though this work focuses mainly on the burst-mode upstream operation, a continuous-mode downstream, typically transmitted in another waveband, can be inferred to perform not worse as long as transmitting and receiving subsystems at the optical line terminal (OLT) and the ONU are similar.

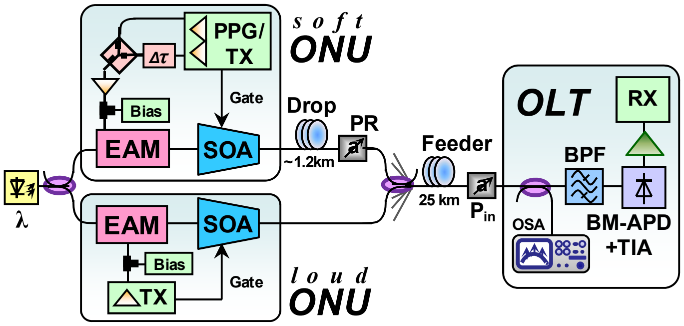

Fig. 1. High bit-rate TDM-PON featuring 20 Gb/s 4-PAM transmission with chirped transmitters.

The seed wavelength at 1558 nm was split and modulated at each ONU by an electro-absorption modulator (EAM). A semiconductor optical amplifier (SOA) was used as optical gate to suppress, by more than 40 dB, light emission during the TDM off-state of the ONU, which would cause crosstalk to other ONUs [5]. In principle this SOA can be avoided in case of having a strong enough laser diode, by simply gating the optical light source itself. An electrical 4-PAM signal was generated to drive the EAM at the soft ONU, for which several reported BER measurements have been performed. The electrical 4-PAM signal of the soft ONU was generated by multiplexing two pseudo-random bit sequences of length 2^{11}-1 in an electrical power combiner. A delay was introduced to one path in order to de-correlate the two PRBS streams. A preamble of alternating mark and space bits was added before the payload data. The loud ONU was transmitting a 10 GHz clock signal rather than data due to lack of a second electrical 4-PAM generator. The gating signal of the SOAs was chosen to have a guard time of 50 ns between the rising edge of the gate and the preamble of the data packet. The upstream packets were then launched from the ONUs with a power (P_{Launch}) of 3dBm.

The optical distribution network contained a short standard single-mode drop fiber span, which was also used to coarsely interleave the packets from the different ONUs according to the chosen TDM frame. A longer 25 km feeder fiber connected the power splitter, emulated by a 50/50 coupler, to the OLT. Two attenuators were added to the PON, for determining the packet power ratio (PR) between the two ONUs (i.e. loud/soft ratio) and the PON loss budget.

The OLT receiver contained an optical band-pass filter to suppress amplified spontaneous emission of the ONUs and a burst-mode receiver based on an avalanche photo diode (APD) with a trans-impedance amplifier. The 10 Gbit/s burst-mode trans-impedance amplifier (BM-TIA), presented in [6], incorporates a fast automatic gain control (AGC) and a gain-locking function. The APD multiplication factor M was set to 9 and the overload was found to be higher than –5 dBm, but higher input levels are avoided to avoid damaging the APD. When a burst ends, the BM-TIA is set to a high trans-impedance gain for maximum reception sensitivity $P_{Sens,RX}$. During the preamble, the trans-impedance gain is adapted by the fast AGC based on the new incoming burst level. After the gain control is settled, the BM-TIA trans-impedance gain is finally locked to avoid unwanted gain fluctuations for the burst payload. As the AGC circuit senses the input signal amplitude, it works for both, non-return-to-zero (NRZ) and 4-PAM signals.

Due to the lack of electrical equipment for the demultiplexing of the received 4-PAM signal into its binary tributaries, the received electrical 4-PAM data was stored with a 50 GS/s real-time scope for the purpose of symbol-by-symbol signal decoding with a multi-level slicer. No post-distortion or additional post-processing technique was applied to the received signal. A practical solution for application in a real PON can be a combination of a limiting and a differential amplifier in order to subsequently extract the most and least significant tributary of the quaternary PAM.

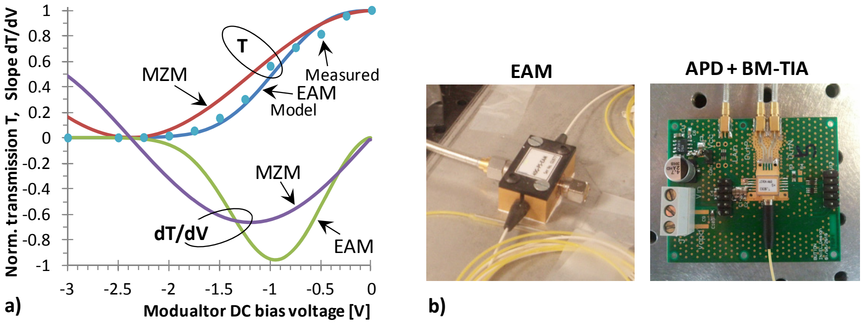

Fig. 2. (a) Normalized non-linear EAM transfer function in comparison to a MZM, (b) in-line EAM device and BM-TIA used for the experiment.

Multi-level intensity modulation requires an optical transmitter response that is linear for a wide range of its input. This can be a problem especially for EAMs, since the transmission function of such modulators is highly non-linear in their low and high bias regime. The typical transfer function of an EAM follows the applied electrical drive V according to Eq. (1):

$$T_{eam}(V) = (1-\varepsilon_{\min})\exp\left[-\left(\frac{V}{V_a}\right)^{\alpha}\right] + \varepsilon_{min} \qquad (1)$$

where $\varepsilon_{\min}$ is the minimum extinction and V_a and α are fitting parameters [7]. Figure 2(a) shows the measured and modeled ($V_a = -1.12$V, $\alpha = 2.7$) transmission T of the utilized EAM as well as the respective curves for a Mach-Zehnder modulator (MZM), whose V_π is adjusted to have the same modulation index per electrical drive as the typically more efficient EAM [8]. The transmission has been normalized to the intrinsic modulator loss. As can be seen, the EAM has a constant and steep slope *dT/dV* only for intermediate bias values. Compared to a MZM the linearity of the EAM is clearly worse and leads to signal distortions when large-signal modulation is applied. This is indicated by the analytical 4-PAM eye diagrams in Fig. 3(a) and is further evidenced by the accompanying measured eye diagram at the transmitter output. In the latter case, additional distortions are visible such as an overshoot due to electrical reflections in the driving circuitry, operation of the SOA at the border of linear and saturated regime, and inhomogeneous eye widths due to difference in rise and fall time of the electronics.

The modulation extinction ratio (ER) and eye asymmetry resulting from a driving signal with limited swing is presented in Fig. 3(b) as a function of the EAM bias V_b. The asymmetry for 4-PAM is here defined as the difference between the smallest and largest eye opening with respect to the largest eye opening. In principle, a high ER requires operation with a highly negative bias in order to provide good light extinction. This, however, causes an excess insertion loss (IL) due to the interplay of limited swing and finite modulation efficiency, resulting in extra losses since the maximum of the EAM transfer function cannot be reached. In addition, a high or a low bias raises issues regarding the asymmetry due to large-signal operation in an area of the transfer function that does not have a constant slope (Fig. 2). An optimum area of operation can be found around the moderate bias V_{opt}, for which the asymmetry has a minimum that is given by the stretched middle eye. Though this minimum for the EAM is still worse compared to a MZM, it is a good trade-off having also a high ER >12 dB and still relatively low excess IL of ~1 dB. The optimum can also be derived by analyzing the harmonic distortion caused by the EAM non-linearity giving nearly the same result. However, for 4-PAM signals, the proposed optimization method provides insight in a more intuitive way.

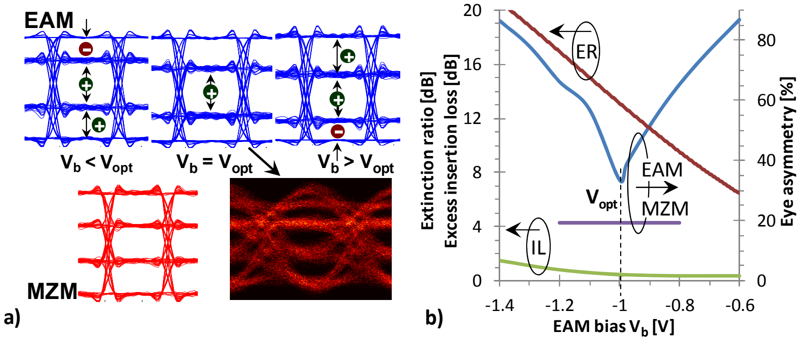

Fig. 3. (a) Eye asymmetry depending on the EAM bias voltage and (b) EAM bias voltage selection trade-offs with respect to eye asymmetry, extinction ratio and excess insertion loss

In order to compensate for the non-linear transfer function of the EAM it is necessary to pre-distort the electrical 4-PAM signal by means of simply varying the amplitude ratio of the constituent binary PRBS signals before the electrical power combiner. In case that the optimal EAM bias voltage Vopt is chosen, this will cause a variation in the height ratio of the outer and middle eye of the electrical 4-PAM signal. On the other hand, since this will lead to increase sensitivity to noise and impairments in the driving circuitry, signal pre-distortion can be used only up to a certain degree. Note that operation solely in the linear regime of the EAM with a reduced modulation swing leads to a strongly reduced modulation extinction ratio and, consequently, to a large reception penalty.

The electrical driving signal of the EAM used in the experiment was pre-distorted by 67% (according to the definition for the asymmetry given above) in order to account for the non-linear transmitter circuitry, which also includes an RF amplifier that is not optimized in its linearity. The driving voltage of 1.4 V_{pp} leads to an ER of 13.2 dB and underlines the advantage of an EAM as more energy efficient modulator than a MZM, providing at the same time a smaller form-factor and the possibility for photonic integration with the laser and the subsequent gating SOA. The transmitted 4-PAM signal is shown in Fig. 3(a). The lower eye was left slightly increased in order to make the 4-PAM robust against bandwidth limitations and chromatic dispersion.

3. Results and discussion

The performance of the 20 Gb/s TDM 4-PAM was evaluated in terms of compatible loss budget (LB) and PR, and was compared with 10 Gb/s NRZ transmission. The NRZ and 4-PAM spectra are presented in Fig. 4(a) and are normalized to the peak spectral component. Figure 4(a) shows that the data rate of 20 Gb/s can be supported without spectral widening of the upstream signal. As a consequence, 20Gb/s 4-PAM modulation does not introduce a penalty due to dispersion in the transmission path (compared to 10Gb/s NRZ), as it would be the case for 20Gb/s NRZ modulation. Burst-mode was applied according to a 10 μs long TDM frame with a loud and a soft data packet and a 100 ns guard time between them as shown in Fig. 4(b). The soft packet was 4 μs long.

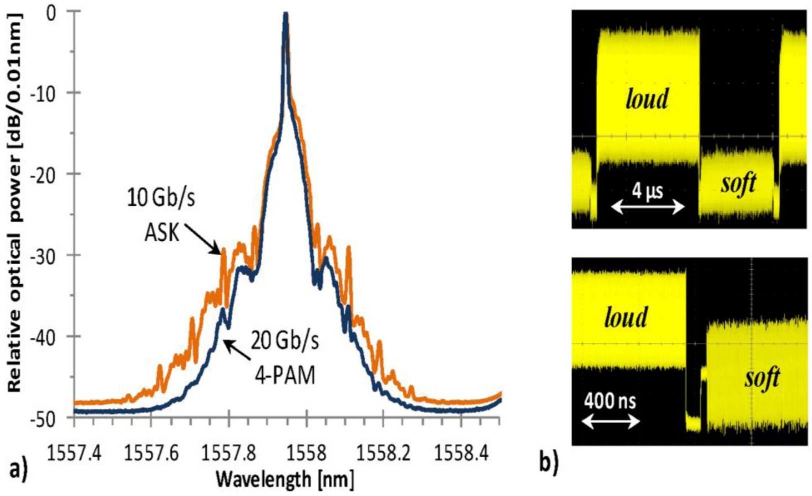

Fig. 4. (a) Signal spectra for NRZ and 4-PAM upstream (b) Loud-soft bursts and timing.

The BER measurements for a configuration with a single ONU and two ONUs with equal packet power are presented in Fig. 5(a). With respect to 10 Gb/s NRZ transmission, the 20 Gb/s TDM 4-PAM experiences a power penalty of 8.1 dB, which is primarily explained by the reduced eye openings in case of a four-level signal, which would cause a penalty of 5-8 dB depending on the exact spacing between the levels and their optimization towards dispersion tolerance or signal-spontaneous beat noise [9]. The remaining penalty is explained by the residual asymmetry in the eye and imperfection in the electrical driving circuitry deriving mainly from reflections at the RF power combiner. The latter could be avoided by using a Digital-to-Analogue Converter for the multiplexing of the binary tributaries into the 4-PAM signal.

Addition of a second ONU and 25 km of distribution fiber in the feeder section in order to provide realistic PON conditions incurred a penalty of just 0.4 dB while the BER became more sensitive to the decision point chosen after sampling at the real-time oscilloscope. The compatible loss budget, defined as the difference between upstream launch and reception

#177198 - $15.00 USD Received 1 Oct 2012; revised 17 Nov 2012; accepted 19 Nov 2012; published 28 Nov 2012

sensitivity, is 21.2 dB for a single ONU in case of employing Reed-Solomon RS(255, 223) forward error correction (FEC). This fits to a TDM-PON with 1:32 split and 25 km reach, as there is still a small power margin of 0.3 dB. Table 1 summarizes the characteristic power levels and loss budget values.

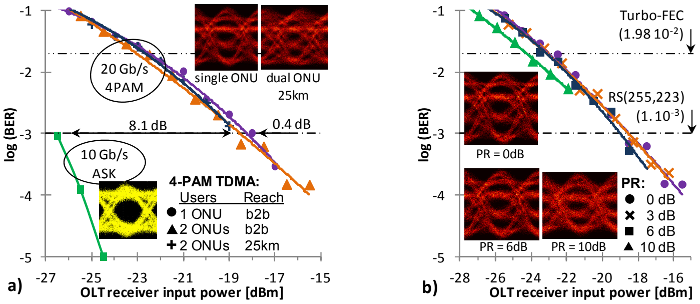

Fig. 5. (a) Comparison between 10 Gb/s NRZ and 20 Gb/s 4-PAM transmission, and (b) BER for 4-PAM at different packet power ratios between loud and soft packets.

The BER for the weak packets in case of different PRs between loud and soft ONU is presented in Fig. 5(b). There is no penalty for a PR up to 6 dB compared with equal-power packets. In case of 10 dB power difference there was a limitation in the power budget; however, the BER did not worsen. Higher loud-soft ratios were not evaluated to avoid overloading the BM-TIA (specified at −5dBm) during the loud bursts. In case that a stronger turbo-FEC is used [10], a loss budget of 27.3 dB is compatible and fits to a scenario with extended 1:64 split in the tree once the high 6.4 dB power margin is eroded for the purpose of split extension. This confirms that 4-PAM is a good candidate for high bit-rate TDM PONs with high dynamic range and high user share.

Table 1. Compatible optical budgets and power margins for a 1:32 split, 25 km reach TDM-PON.

Scenario	**10 Gb/s** ***NRZ***	**20 Gb/s** ***4-PAM***			
ONUs:	single	single	dual	dual	dual
PR [dB]	-	-	0	6	10
P_{Launch} [dBm]	3	3			
$P_{Sens,RX}$ [dBm]	–26.6	–18.2	–18.5	–19	–24.3*
$LB_{Compatible}$ [dB]	29.6	21.2	21.5	22	27.3*
LB_{PON} [dB	20.9				
Power Margin [dB]	8.7	0.3	0.6	1.1	6.4*

*Values are listed for the case of employing turbo-FEC at the OLT receiver.

4. Conclusions

A 20 Gb/s quaternary TDM-PAM access network has been demonstrated as upgrade path for legacy PONs. A loss budget of 27.3 dB can be supported in combination with a high loud-soft power ratio of 10 dB. Chirped, non-linear transmitters and 10 Gb/s burst mode receivers are compatible.

Acknowledgments

This work was supported by the European Commission through FP7 EURO-FOS NoE, the Greek Secretariat for Research and Technology project WisePon (09ΣYN-71-1155) and the Agency for Innovation by Science and Technology in Flanders (IWT).

#177198 - $15.00 USD Received 1 Oct 2012; revised 17 Nov 2012; accepted 19 Nov 2012; published 28 Nov 2012