100 GBd Dispersion-Tolerant Downstream PON with 35 dB Power Budget using APD and Low-Complexity Equalization

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Abstract *A 100G downstream dispersion-tolerant PON with a back-to-back power budget of 35 dB based on combining optical and electrical duobinary signaling using a 25G APD is experimentally demonstrated. Increased reach of 50G PON with optical duobinary is also demonstrated using a real-time setup.*

Introduction

The 50G time division multiplexed passive optical network (TDM-PON) standard has recently been published in ITU-T G.9804 [1]. We have investigated increasing the line-rate of PON to 100 Gb/s by using quaternary pulse amplitude modulation (PAM4) and flexible PON concepts [2,3]. The advantage of 100G PAM4 is that it can re-use the same optical components as 50G non-return-to-zero (NRZ) modulation, but this comes at the cost of reduced signal to noise ratio (SNR) due to the four signal levels instead of two, as well as more stringent linearity requirements. The optical power penalty between 50 Gb/s NRZ and 100 Gb/s PAM4 is typically found to be 8-9 dB in experiments [2-4]. Fiber non-linearities like stimulated Brillouin scattering (SBS) will limit the maximum transmit power; additionally, PAM4 suffers from multiple path interference (MPI) issues [5]. Moreover, when a semiconductor optical amplifier (SOA) is used as booster for PAM4, its gain will be restricted since it cannot be driven into saturation due to the non-linear patterning effects [6]. Because of all these issues, it is not easy to achieve a C+ power budget class (32 dB) in the case of 100G PAM4 [7,8]. An alternative to intensity modulation and direct detection (IM-DD) PON is coherent PON which has the capability to enable large power budgets with high dispersion tolerance. So far, its cost and power consumption are not in line with PON expectations, especially at the ONU side. Therefore, it makes sense to explore means to still use IM-DD technology for 100G, which is much more cost-effective and energy efficient [9,10]. A straightforward way would be to double the rate to 100 Gb/s NRZ, however much higher bandwidth (BW) components will be needed while dispersion tolerance will be further reduced by a factor of four making it challenging to achieve a reach of 20 km for most practical downstream wavelengths.

In this paper we experimentally validate optical duobinary (ODB) combined with electrical duobinary conversion at the receiver (EDB) to achieve 100G downstream PON transmission in a low-complex and cost-effective way. ODB has several features which make it a suitable scheme to solve the challenges of further increasing the PON rate beyond 50 Gb/s [11,12]. ODB can use lower BW components at the transmit side while still allowing conventional direct detection at the more cost-sensitive optical network unit (ONU) receiver (Rx) side. Also, ODB was found to be more dispersion tolerant then conventional NRZ [11]. ODB is a carrier suppressed signal, in contrast to NRZ and PAM4, which enables launching higher average powers without incurring penalties due to SBS. ODB however does require a single Mach-Zehnder modulator (MZM) because intensity and optical phase need to be modulated. Yet, this is still much less complex than an IQ MZM needed for coherent transmission. With the upcoming low-voltage and cost-effective MZM technologies, like Thin Film Lithium Niobate [13] it becomes practical to use ODB for downstream while still using simple and cost-effective direct detection at the ONU side. As the downstream wavelength we selected λ=1342 nm which is adopted for 50G PON downstream [1] and therefore provides a good comparison. At the ONU side we use a 25G class avalanche photodetector (APD) for low cost and power consumption. Even though ODB alleviates the bandwidth requirements at the transmit side, at the receive side we need to counteract the low bandwidth of the APD as well for 100G detection. For this we propose to adopt low complex equalization with 3-level Electrical Duobinary Detection (EDB) [14]. To the authors knowledge this is the first ever demonstration of a transmission based on ODB combined with EDB conversion at the receiver. For the 100G NRZ and 100G ODB/EDB experiments we use a 20-tap FFE which is practically feasible and in-line with upcoming 200G SerDes (100 Gb/s) technology for IEEE 800GbE and 1.6 TbE data center transceivers [15]. We also compared results with 100G PAM4 transmission using the same setup.

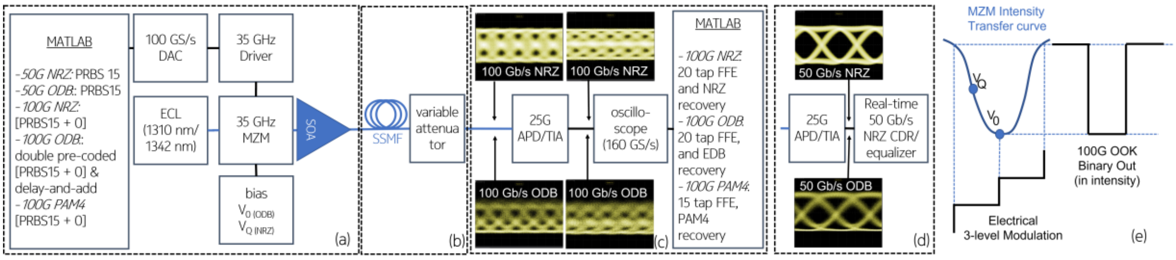

Fig. 1: (a): transmitter setup. (b): ODN emulation. (c): 100 Gb/s receiver setup based on offline data recovery. (d): 50 Gb/s receiver setup based on real-time data recovery. Eye-diagrams inserted for each case. (e): Illustration of Optical-Duobinary (ODB) modulation on MZM.

In addition to the 100G ODB/EDB experiments, we also validated extended reach 50G ODB, which is becoming of increased interest to operators. As proof of implementation feasibility of ODB using APD-based receivers and off-the-shelf clock-data-recovery (CDR) this has been performed using a real-time CDR with integrated 15 tap FFE with and without 1 tap DFE equalizer and on-chip bit error rate (BER) checkers.

Experimental Setup

Fig. 1 shows the experimental setups that were used. On the transmit side 50 Gb/s, 100 Gb/s NRZ, and 100 Gb/s PAM4 waveforms are generated in MATLAB using a PRBS15 (length $2^{15}-1$) pattern for the real-time 50G reception, while for offline measurements the sequence is padded with an additional zero (total length 2^{15}). Since we perform ODB transmission as well as EDB detection for 100G ODB/EDB, this signal is pre-coded two consecutive times. For ODB a delay-and-add operation (partial-response filtering), converting the NRZ into a lower bandwidth 3-level signal is applied before uploading to a 100 GS/s digital to analog converter (DAC). The signal is then amplified by a 35 GHz driver and modulated on a MZM biased at the null (V_0) for ODB and biased at quadrature point (V_Q) for NRZ and PAM4. The waveforms are modulated onto a λ=1342 nm optical carrier generated by an external cavity laser (ECL) and boosted by an SOA. Signals are transmitted over standard single mode fiber (SSMF) and attenuated (to emulate the optical distribution network – ODN) and detected with a 25G class APD packaged with a linear transimpedance amplifier (TIA). For the 100 Gb/s cases the signals at the output of the APD/TIA are captured with an oscilloscope at 160 GS/s and offline processed using MATLAB for simple FFE based equalization and Bit-Error-Rate (BER) counting of the signal. For the 50 Gb/s cases the signals are received using a real-time CDR with integrated equalizer and on-chip BER checkers after detection with the APD/TIA.

Results

Fig. 2(a) shows the BER results of 100G NRZ, 100G PAM4 and 100G ODB/EDB back-to-back (b2b) and after 20km of SSMF for the ODB/EDB case. It can be observed that 100G NRZ already has a very high BER $>6\cdot10^{-2}$ for the b2b case. The performance of 100G NRZ is limited by the receiver bandwidth as well as bandwidth limitations at the transmitter. 100G ODB with EDB detection has much better performance with a b2b sensitivity of -19.5 dBm at BER=$1\cdot10^{-2}$. After 20km of fiber the dispersion penalty is ~2.3 dB. Since responsivity of our APD is optimized for 1310 nm due to its AR-coating, an even better b2b sensitivity of -20.8 dBm for

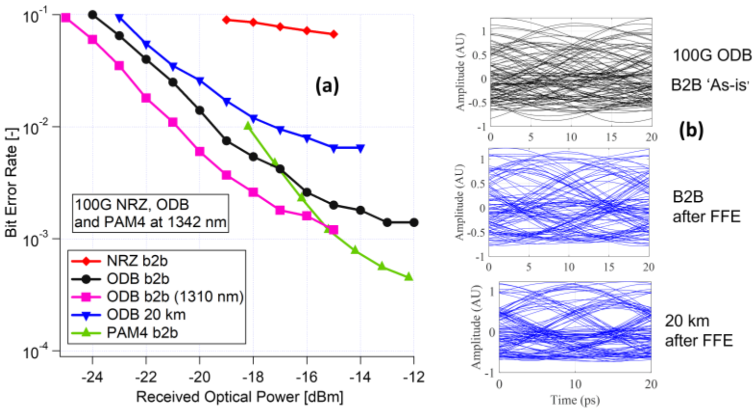

Fig. 2: (a) Experimental results for 100G NRZ, 100G PAM4 and 100G ODB, b2b and after 20km of fiber for 100G ODB (b) 100G ODB eye-diagrams before and after 20-tap FFE equalization, b2b and after 20km of fiber

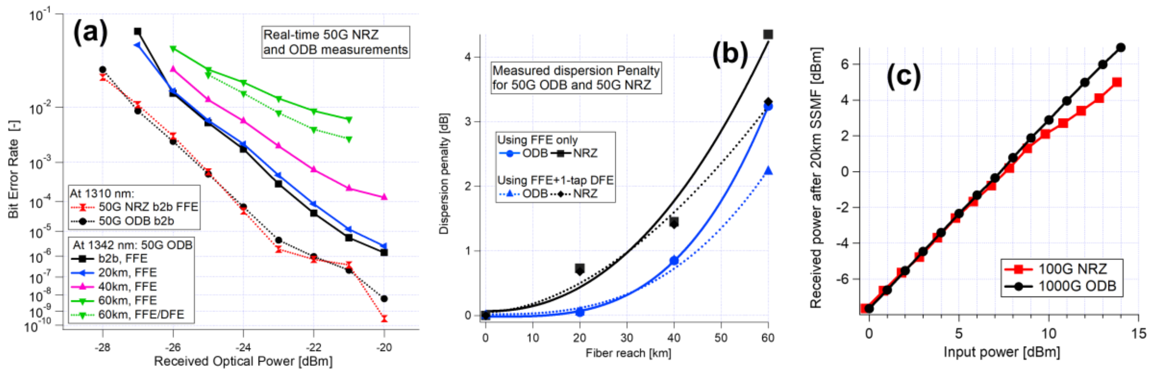

Fig. 3: (a) Experimental BER results of 50G ODB and NRZ. (b) Dispersion penalty for 50G PON extended reach applications. (c) Measured launch power and reflected power for 100G ODB compared to 100G NRZ

λ=1310 nm at BER=$1{\cdot}10^{-2}$ can be obtained for 100G ODB/EDB. We find a ~1.3 dB b2b receiver sensitivity improvement for 100G ODB/EDB over 100G PAM4, which is along expectations given the fewer signal levels in the ODB/EDB case. Fig. 2(b) shows the measured b2b eye-diagrams as received and after 20-tap FFE equalization for 100G ODB at −16 dBm.

Fig. 3(a) shows the BER results of 50G ODB for b2b and after fiber transmission. It can be observed that fiber reach up to 60 km can be achieved while the BER is still below the default G.9804.2 hard-decision FEC threshold of $1{\cdot}10^{-2}$. Fig. 3(b) shows the measured dispersion penalty as a function of fiber reach. A 2.2 dB dispersion penalty was found for 50G ODB after 60 km SSMF with the FFE/DFE equalizer. For comparison, 50G NRZ with the same MZM has been measured as well. ODB enables a 1 dB better dispersion penalty than NRZ after 60 km SSMF with both 15 tap FFE only and 15 tap FFE + 1 tap DFE. The dispersion penalty of 50G NRZ is relatively low as well due to the reduced chirp of the MZM used (α=-0.2) compared to a conventional Electro-absorption Modulated Laser (EML) with α=+0.5 [3] but ODB modulation further improves the performance.

To enable high power budget classes >29 dB, high transmit powers are required. Since ODB has a suppressed optical carrier, high average powers, subject to presence of a booster amplifier, can be launched without incurring penalties due to SBS. Fig. 3(c) shows the received power after 20 km SSMF versus average input power for 100G NRZ and 100G ODB. It can be observed that SBS penalty becomes significant for 100G NRZ (which will also be the case for 100G PAM4) at >10 dBm launch power. For 100G ODB we can transmit 14.5 dBm power (limited by our setup) without significant penalty. For 100G ODB at λ=1310 nm in the b2b case we obtained a power budget of 35 dB. Assuming 1 dB penalty for diplexer losses and considering implementation margins a 32 dB C+ budget class is attainable for 100G ODB PON with EDB detection using a 25G class APD and feasible low complexity 20-tap FFE equalization. For upstream we envision asymmetric 50G service for now, however the ODB scheme is also very compatible with current 50G NRZ burst-mode receiver technology [16] and provides a simple upgrade path when cost of MZM comes down more.

Conclusions

For the first time an experimental demonstration of ODB transmission in combination with EDB conversion at the receiver was shown to enable 100G IM/DD PON. The combined ODB/EDB scheme is very tolerant to bandwidth limitations, at the transmitter as well as the receiver. Compared to 100G PAM4 and 100G NRZ, a higher launch power and a better receiver sensitivity was achieved for ODB/EDB. A b2b optical power budget of 35 dB at BER=$1{\cdot}10^{-2}$ (assuming hard decision FEC) and 36 dB at BER=$2{\cdot}10^{-2}$ (assuming soft-input FEC) was achieved for 100G ODB/EDB. A reach of 20 km at λ=1342 nm was obtained with 2.3 dB dispersion penalty using a 25G grade APD and simple 20-tap FFE equalization for 100G ODB/EDB. These results show the potential for using the ODB/EDB scheme for future very high speed cost-effective ≥100G PON systems.

Secondly, ODB without EDB was validated for 50G PON to enable extended reach. As already stated, ODB is more dispersion tolerant compared to NRZ but can still be recovered as an NRZ signal after direct detection. 50G ODB was experimentally validated using a real-time off-the-shelf CDR integrated with equalizer (15-tap FFE, 1-tap DFE). In this experiment a reach of 60 km SSMF at λ=1342 nm was obtained with 2.2 dB dispersion penalty, which is a 1 dB improvement relative to conventional 50G NRZ measured with the same setup.

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