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200 Gb/s/λ Bidirectional Coherent PON Solutions Demonstrated over Field Installed Fiber

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***Abstract*—We demonstrate 200 Gb/s bidirectional coherent PON solutions using a simplified optical network unit (ONU) over 19 km of field-installed fiber. The ONU receiver is a single-polarization heterodyne detector with either a balanced or a single-ended photodetector and the transmitter is based on dual-polarization electro-absorption modulated laser (EML). The optical terminal unit (OLT) uses standard dual-polarization coherent transceivers. The downstream solutions achieve 37 dB and 30.5 dB power budget for the receiver with balanced and single-ended photodiodes, respectively. For the upstream, two line rates have been investigated: 200 Gb/s/λ for symmetrical transmission and 100 Gb/s/λ for asymmetric transmission achieving a power budget of 30.1 dB and 40.9 dB respectively.**

***Index Terms*—Passive optical network (PON), Optical network unit (ONU), Optical line terminal (OLT), Coherent transceivers.**

I. INTRODUCTION

PASSIVE optical networks (PON) are the primary solution for fiber based access networks [1], with successive standards allowing for increased data rates to be transmitted over the installed optical distribution network (ODN). Following the standardization in 2021 of the 50 Gb/s Higher Speed PON (HS-PON) by ITU-T [2], the research interest is shifting towards the next generation: Very High Speed PON (VHSP) [3]. This technology is expected to make similar linerate steps as previous successful generations did, from G-PON (2.5 Gb/s) to XG-PON (10 Gb/s) and to HS-PON (50 Gb/s), and as such the most likely linerate is 200 Gb/s.

To date all PON technologies have made use of intensity modulation/direct detection (IM/DD) technology, since it allows for very cost-effective modulation and detection. However the penalty due to chromatic dispersion (CD), which scales quadratically with symbol rate, presents a significant challenge for an IM/DD 200 Gb/s PON. Given HS-PON requires digital signal processing (DSP) to mitigate the CD penalty to an acceptable level [2], the same DSP would result in a prohibitive penalty for VHSP, using on-off keying (OOK).

While there have been demonstrations of 200 Gb/s/λ IM/DD solutions, from these experiments it is clear that IM/DD is being pushed to it's ultimate limit on a single wavelength transmission. These demonstrations use higher order modulation formats (PAM4), and either high-cost components, such as Raman-amplifiers and circulators [4], or large Volterra equalizers [5]. An alternative approach investigated recently is using polarization multiplexing in IM/DD, however this requires receiver side polarization control [6], which is currently challenging to integrate. Due to the aforementioned difficulties of IM/DD, coherent PON has been gaining significant attention, and is considered as one of the possible solutions for VHSP [7]. However, a full coherent link has significantly higher complexity than IM/DD and as such the transceiver cost is magnitudes higher. Since PON systems are very cost sensitive, especially on the optical network unit (ONU) side, a full coherent PON is likely too costly for widespread adoption.

Recently simplified coherent solutions have been investigated. Here it is worth splitting the options into two main categories. Simplified downstream transmission, where the receiver architecture is simpler, and upstream transmission where the transmitter is made simpler. This is done to exploit the asymmetry of the PON architecture, whereby the ONU is more cost sensitive than the optical line terminal (OLT). In terms of downstream transmission, the simplification of the ONU comes at the cost of increased bandwidth requirement of the components, compared to full coherent. Using heterodyne detection, and single polarization detection can reduce the number of I/O ports from 4 to 1 in the receiver [8]. These simplified coherent receivers have been investigated in terms of the sensitivity/complexity trade-off extensively [9]. Alamouti coding elliminates need for receiver side polarization control, as the transmitted information is redundant in both polarizations and can be recovered without excess penalty [10].

This paper is an extension to the work presented at Optical Fiber Communications Conference 2024 [11]. This letter provides more results and analysis for symmetric 200 Gb/s bidirectional transmission. In addition, we investigate low-cost approaches for asymmetric PON with 100 Gb/s upstream transmissions. In the past all PON technologies have started with half rate upstream transmission compared to the downstream speed, and as such this letter fills a gap in current research into 200 Gb/s coherent PON research. The 100 Gb/s upstream solution achieves a power budget of 33.4 dB using single-polarization 50 Gaud PAM-4 and 40.9 dB (with booster SOA) or 29.8 dB (without booster) using 50 Gbaud DP-OOK showing the high loss budget/low-cost capabilities of the system.

II. EXPERIMENTAL SETUP

Experimental investigations can be split into downstream and upstream transmission. In the downstream transmission,

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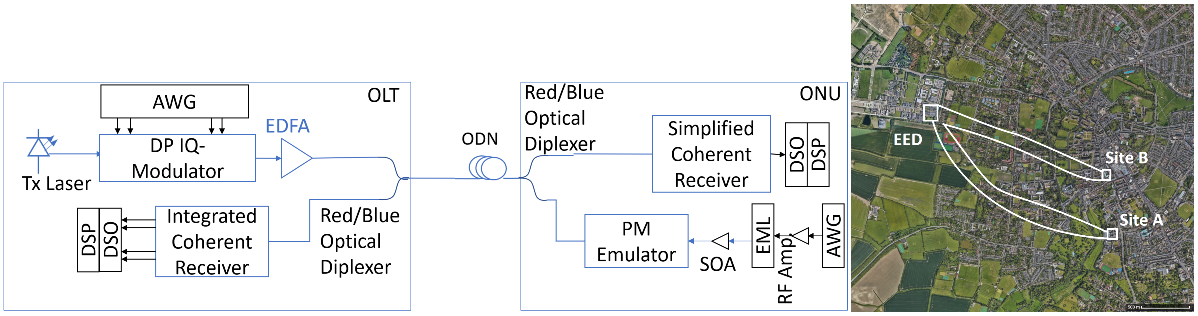

(a) (b)

Fig. 1: (a) Experimental setup for 19 km bidirectional transmission. (Arbitrary signal generator (AWG), optical line terminal (OLT), digital sampling oscilloscope (DSO), digital signal processing (DSP), electro-absorption modulated laser (EML), semiconductor optical amplifier (SOA), optical network unit (ONU)). (b) Geographical connection of field installed fiber

a 50 GBaud, 16 QAM, Alamouti coded signal is used to achieve 200 Gb/s/λ. This is generated offline, pulse shaped and predistorted [12]. It is subsequently uploaded to an arbitrary waveform generator (AWG), operating at 100 GSa/s. The optical modulation is performed by a dual-polarization IQ modulator of analog bandwidth of 40 GHz. Launch power is set by an erbium-doped fiber amplifier (EDFA). There are two receivers investigated in this experiment. Single polarization heterodyne receiver, with a balanced photodiode, and with a single ended photodiode, often referred as the minimal coherent receiver. These receivers were constructed of discrete components. Photodiodes have 70 GHz analog bandwidth, followed by an RF amplifier with 60 GHz bandwidth. Digitization is performed with a digital sampling oscilloscope (DSO) operating at 256 GSa/s, with bandwidth of 70 GHz. Signal is processed offline, using a modified LMS equalizer [10].

The experiment investigates multiple setups for the upstream transmitter. Different setups are shown in figure 1a. For 200 Gb/s/λ transmission, the 50 GBaud PAM4 signal is generated offline. This is uploaded to the AWG, and then modulated by an electro absorption modulator (EAM). Our experiment uses an integrated package of DFB laser with EAM is as an externally modulated laser (EML). Due to equipment availability the polarization multiplexing is emulated using the split delay recombine method [13]. Launch power is set by a semiconductor optical amplifier (SOA). Signal is detected by a class 40 integrated coherent receiver (ICR). The digitization is done by DSO operating at 256 GSa/s, with 70 GHz bandwidth. The signal processing is performed offline [14].

The 100 Gb/s/λ rate was investigated using multiple solutions. Using a single polarization of the PAM4 signal, or alternatively using dual polarization at the same symbol rate, whilst changing the modulation format to OOK.

The signals are coupled into the field installed fiber, and separated again for detection using a red/blue optical diplexer. These devices offer low insertion loss ($\sim$0.9 dB) and high isolation for the wavelengths used in this experiment, thus allowing best case sensitivity and launch power. The field installed fiber is part of the Granta Backbone Network at the University of Cambridge. It consists of two coupled loops from the Electrical Engineering Division (EED on figure 1b), where the signal is transmitted and received, to the Engineering Department Server room (Site A on figure 1b) and the University Information Services server room (Site B on figure 1b). The total length of the fiber link is 19 km, which is a good representation of PON networks typical reach of 20 km. The overall loss in the fiber is 12.7 dB. This large loss is due to the large amount of connectors and splices that are present in the link as it is patched through inside the buildings, as well as the additional splices originating from the urban environment of the field installed fiber. The optical time-domain reflectometer (OTDR) trace of the fiber can be seen in figure 2.

III. RESULTS AND DISCUSSION

The performance of the solutions were evaluated by measuring the received optical power (ROP) at which the bit error rate (BER) is 10^{-2}. This was chosen as it is the HD-FEC threshold of FEC used in HS-PON [2]. The power budget is subsequently derived by performing a sweep of launch powers and comparing the corresponding sensitivity.

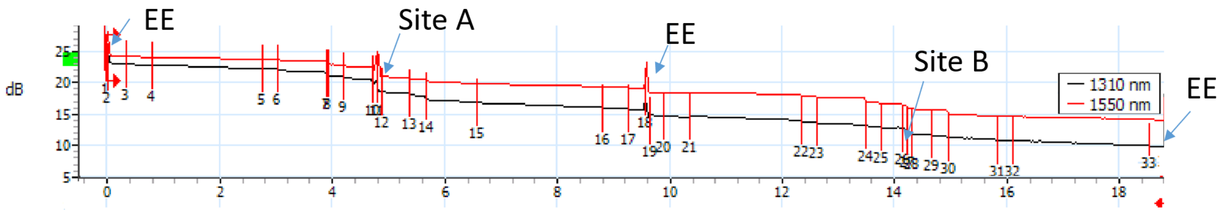

Fig. 2: Plot of the OTDR trace of the field installed fiber

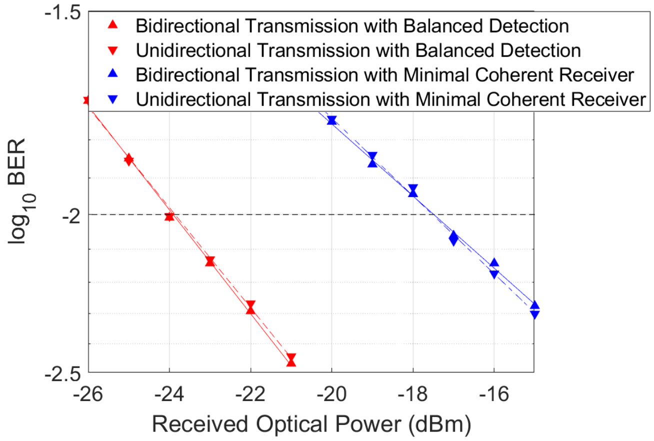

Fig. 3: Sensitivity at optimum launch power for 200 Gb/s/λ downstream transmission

The downstream transmission investigates both the balanced photodiode based approach and the single ended photodiode. The optimum launch power was determined by varying the launch power, measuring the sensitivity and calculating the corresponding power budget. Sensitivity at optimum launch power was found to be -24 dBm for the balanced photodiode case and -17.5 dBm for the minimal coherent receiver, as shown in figure 3. The maximum power budgets were found to be 37 dB and 30.5 dB respectively, as shown in figure 4.

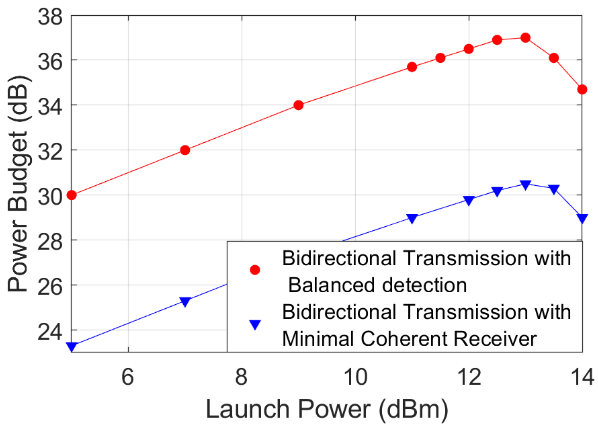

Fig. 4: Power budget for 200 Gb/s/λ downstream transmission

There are two main concepts investigated for the upstream transmission. First of all, the full rate 200 Gb/s/λ transmission, which is achieved using PDM-PAM4 with 50 GBaud symbolrate. The second is the half-rate 100 Gb/sλ transmission, which can be achieved in two main ways. Either by using a single polarization PAM4 transmission, or by using a PDM-OOK transmission, both at 50 GBaud. These solutions explore the tradeoff between component complexity and sensitivity.

The sensitivity at optimum launch power is shown in figure 5. It can be seen that the penalty between OOK and PAM4 transmission using the same setup is much larger than the theoretical minimum. This is due to patterning inside the SOA and limitations inside the EML module. A sensitivity plot for an unamplified transmission is also included. Here sensitivity was measured to be -28.3 dBm, which coupled with the 1.5 dBm output power of the transmission setup, results in a power budget of 29.8 dB. This is in excess of ITU-T N1 class requirements. The power budgets for the amplified transmissions can be seen in figure 6. It can be seen that the OOK transmission experiences less penalty due to gain saturation inside the SOA, and as such higher launch power can be achieved. The maximum analysed launch power is 13 dBm, which is the limit of the SOA used in the experiment. It can be seen from the graph that the DP-OOK transmission achieves 40.9 dB power budget, well in excess of ITU-T E2 class. Single polarization PAM4 achieves 33.3 dB, whereas the DP-PAM4 achieves 30.1 dB.

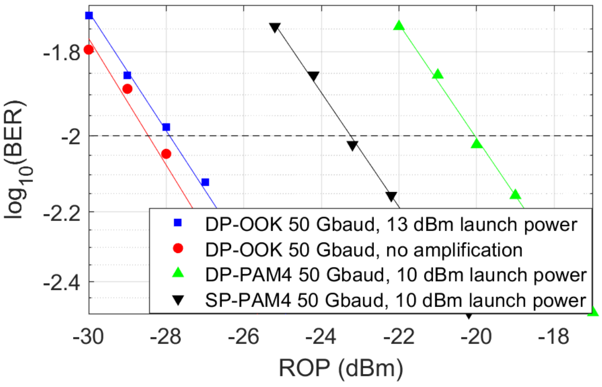

Fig. 5: Sensitivity of upstream transmission

The 100 Gb/s/λ transmission offers interesting comparisons, in terms of complexity and power budget. The single polarization approach requires only one digital to analog converters (DAC) and modulator, however it requires an SOA to be able to meet the power budget requirements. SOA can be integrated with the EML [15]. This solution still only achieves N1 class power budget as per the ITU-T specifications, which may not be suitable for all PONs. The other solutions using OOK offer more flexibility. To achieve N1 class power budget, there is no need for optical amplification, which can make the system cheaper, and the transmitted could be constructed using a single laser, which is split onto two polarizations, and these polarizations are modulated separately. Alternatively, if larger power budget is required, the SOA can be integrated. Here, care needs to be taken to ensure that the SOA gain is independent of polarization. There are already solutions offering this capability [16]. The trade-off in the PDM-OOK case is the need for the two DACs and modulators, which increase the cost. The DSP complexity can also be reduced in the PDM-OOK setup, as patterning of the SOA is less present, and due to the simplicity of the modulation format, other sources of nonlinear penalty are less affecting the sensitivity. As such in this case, no maximum-likelihood equalizer is needed to achieve the quoted power budgets.

The upstream transmission needs to be able to deal with a range of issues arising from receiving the time-division multiplexed (TDM) signal from multiple ONUs in a real system. This typically means a large dynamic range and burst mode detection. In the case of the large dynamic range

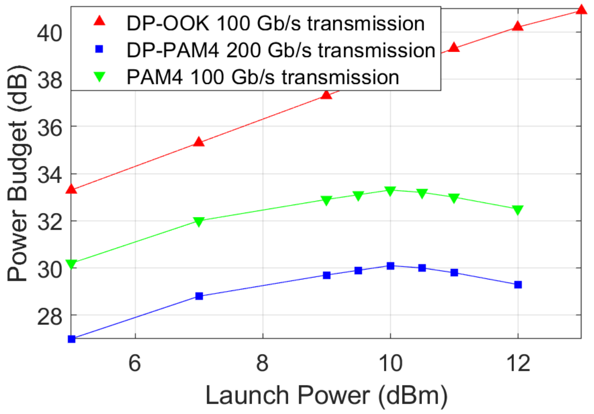

Fig. 6: Power budget of upstream transmission

ONU based power leveling could be used, as the loss of the channel is constant, or alternatively there are recent approaches investigating changing the local oscillator (LO) power to deal with this issue [17]. The burst mode reception capabilities are shown by investigating the convergence time of the equalizer in the upstream detection. It has previously been shown that the equalizer converges within $\sim$200 ns [18], for the single polarization PAM4 case. This time is unchanged in the PDM-PAM4 setup and the PDM-OOK setup.

Showing that there is no penalty from bidirectional transmission using the setup presented above, the measurements at optimum launch power were taken in both bidirectional and unidirectional mode, with no penalty observed. Sensitivity variation with time is a potential concern, as the fiber passes through higher traffic roads, where the mechanical vibration may affect the quality of transmission. However in this case no penalty was observed between experiments conducted in rush hour traffic to overnight.

IV. CONCLUSIONS

We have demonstrated a 200 Gb/s/λ coherent PON solution, which uses Alamouti coding and simplified coherent receivers in the downstream direction, where it achieves power budgets of 37 dB and 30.5 dB for the single polarization heterodyne receiver with balanced photodiode and single ended photodiode respectively. The upstream solution used intensity modulation. For the symmetrical 200 Gb/s/λ transmission PDM-PAM4 signal is used, achieving 30.1 dB power budget. For 100 Gb/s/λ transmission, the single polarization PAM4 signal achieves 33.4 dB, whilst the PDM-OOK transmission achieves 40.9 dB with booster SOA, and 29.8 dB with no booster amplifier.

All of these power budgets exceed N1 class budget. The 200 Gb/s downstream using balanced photodiode and the 100 Gb/s upstream PDM-OOK using SOA amplification exceed ITU-T E2 class power budgets.

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