400 Gbit/s Dual-Wavelength and Dual-Polarization IM-DD TDM-PON with 34 dB Power Budget

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Abstract: We demonstrate a 400G dual-wavelength dual-polarization IM-DD TDM-PON based on optical duobinary modulation with 34 dB back-to-back optical power budget. After 20 km of SSMF we find an optical path penalty below 1 dB.

1. Introduction

Time-division multiplexed passive optical networks (TDM-PONs) have so far relied on adopting technologies initially developed for less cost-sensitive parts of the network where eventual high-volume production of these components leads to low cost that is acceptable for PON. Traditionally, PONs have been based on conventional intensity-modulation and direct-detection (IM-DD) systems using non-return-to-zero (NRZ) on-off keying (OOK) modulation, commonly referred to as NRZ. 50 Gbit/s (50G) PON [1] will be the first PON to use digital signal processing (DSP) in the form of receiver-side equalization, which was adopted from 50 Gbd data center technology [2]. Continuing this trend, a 100G IM-DD NRZ PON seems feasible as well [3]. Nonetheless, eventually IM-DD NRZ PONs will be limited by achievable power budget/launch power and chromatic dispersion (CD) as well as polarization mode dispersion (PMD) [3-5]. To further increase PON data rates, alternative methods besides single channel rate scaling needs to be considered. Another option is to use two wavelengths to enable a 200G NRZ IM-DD PON [3,6,7], where the data rate to each optical network unit (ONU) can be maintained through channel bonding. However, continued scaling beyond two wavelengths seems impractical as well since the optical spectrum is already congested in the O-band due to co-existence requirements [3]. Moreover, four-wave mixing (FWM) will limit the use of multiple wavelengths in the O-band on a narrow grid close to the zero-dispersion wavelength. Therefore, to scale IM-DD PONs beyond 200G, another dimension is needed.

Since a 400G PON is in scope for ITU-T Study Group 15/Question 2 (SG15/Q2) Very High-Speed PON (G.VHSP) applications [8], we will show feasibility of a 400G PON while still relying on IM-DD transmission in this paper. Our system is based on dual wavelength (DW) with dual polarization (DP) per wavelength. DP in combination with direct detection (DD) has also recently been proposed in the context of datacenters for PAM4 800G LR4, see for example [9,10]. Coherent technology also commonly uses DP, here polarization is commonly demultiplexed digitally instead of optically (which is needed for IM-DD with a conventional single detector [9]). However, the requirement for lower power DSP for datacenters applications has motivated research on optical polarization control means for coherent as well [11]. Advances in this area are mainly driven by the increased deployment of photonic integrated circuits (PIC). Therefore, the introduction of photonic integration will likely also be the next step in PON evolution. PICs open the door for cost effective realization of polarization (de-) multiplexing and allow for the integration of multiple wavelengths in a small form factor with low power consumption. We will show that with this architecture, it is possible to realize a 400G PON and demonstrate 34 dB back-to-back power budget and 20 and 40 km fiber reach.

2. Proposed 400G DW-DP TDM-PON Architecture

For the 400G IM/DD TDM-PON we propose to use only two wavelengths, which will result in insignificant FWM penalties, because for two wavelengths there will only be a small power depletion and no interference from the FWM terms with the main channels. Thus, no FWM mitigation is needed. In systems with a larger number of wavelengths, inter-channel FWM mitigation needs to be implemented [12].

The proposed PON is based on optical duobinary (ODB) modulation. ODB has a suppressed optical carrier, which mitigates non-linear effects like stimulated Brillouin scattering (SBS) and cross-gain modulation (XGM) in SOAs [13]. ODB is also very tolerant to CD and limited bandwidth, which enables use of more cost-effective components and low complexity DSP as we also showed in [4] for a single channel 100G IM-DD TDM-PON.

The use of only two wavelengths simplifies co-existence with deployment of XG(S), 25G and 50G PON on the same fiber plant. We propose 1314 nm and 1320 nm as the downstream wavelengths which is a feasible trade-off between CD penalties and needed space between wavelength bands for wavelength multiplexing and de-multiplexing. The use of two wavelengths allows for an easy upgrade path by deploying a 100G PON at 1320 nm [3] first and upgrading this to a 200G PON by adding the 1314 nm wavelength. Finally, a 400G PON can be enabled

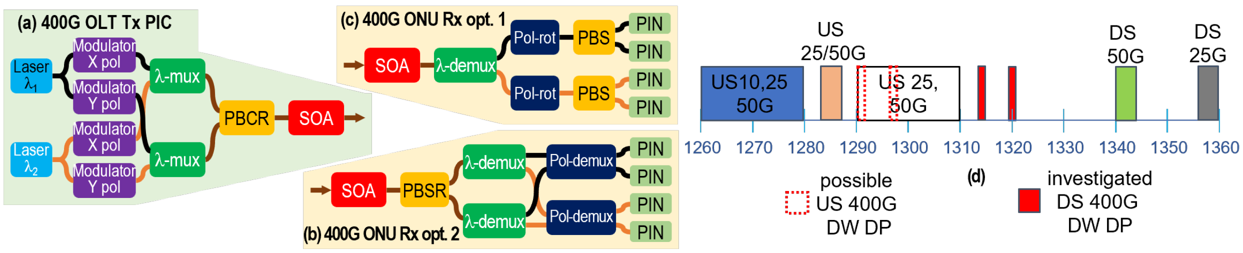

Fig. 1. 400G DW-DP transmitter (a) and receiver options (b,c). Pol rot – polarization rotator, pol demux – polarization demultiplexer. (d) XG(S), 25G and 50G PON wavelength plan with proposed wavelengths for 400G DW-DP PON.

by introducing DP. For the upstream it makes sense to select the wavelengths below the zero-dispersion window (1300-1324 nm) such that the desired co-existence with legacy PONs is achieved, see Fig. 1(d).

Fig. 1(a) and 1(b) show integrated DW-DP transmitter and receiver architectures which align well with silicon-photonics technology as proposed in [9]. Fig. 1(c) shows another possible option for the DW-DP receiver based on more discreet or hybrid technology. For lowest complexity we will focus on DD using a single detector instead of a more complex Stokes-based DD receiver [14], so polarization demultiplexing needs to be done in the optical domain [9]. Due to the large optical power budget requirement of PON, we envision the use of SOAs as booster and as pre-amplifier for the DW-DP PON transceivers. The use of a SOA-PIN based receiver enables absorption of the optical losses introduced by the components needed to introduce polarization multiplexing. Another key subsystem enabling dual polarization with direct detection is a polarization tracker, composed of a fast endless (reset-free) polarization demultiplexer with a feedback system [10]. Recently there have been several demonstrations of on-chip polarization trackers, see for example [11].

3. Experimental Setup

Fig. 2a depicts the experimental setup for the transmitter and receiver side to validate our proposed 400G PON architectures. At the transmit side, two external cavity lasers (ECLs) emitting at 1314 nm and 1320 nm are combined and then split over two Mach-Zehnder modulators (MZM). Each MZM is biased at null and modulated with a differential encoded 100 Gb/s NRZ bit pattern, which is converted to an electrical duobinary (EDB) waveform, uploaded to a digital to analog converter (DAC) and amplified with an RF amplifier. A 2^{15} pseudo-random binary sequence (PRBS15) pattern with an extra zero inserted is applied for the polarization under test while random data is provided to the MZM for the other polarization to ensure that both polarizations can be distinguished at the receiver. After this, the two signals are aligned using a manual polarization controller (PC) to the slow axis of the polarization-maintaining (PM) fiber and combined using a pigtailed polarization beam combiner (PBC), which is designed to combine the two orthogonal polarizations into a single common fiber. Optical powers of the four channels (two wavelengths and two polarizations) are equalized to within 0.5 dB and boosted with an SOA to +11.1 dBm total power (+7.9 dBm in one channel case). The signal is then transmitted over 0, 20, or 40 km of standard single mode fiber (SSMF) and attenuated to emulate the optical distribution network (ODN) losses.

At the receiver side, the polarization under test is aligned to the receiver polarization beam splitter (PBS) axis using a PC after which it is split into its orthogonal linear polarization components. Each orthogonal polarization is amplified by an SOA (which has a polarization dependent gain) after which it passes through a 1.3 nm optical filter centered at either 1314 nm or 1320 nm to select the wavelength and remove the out-of-band noise and finally gets detected by a PIN photodetector followed by a transimpedance amplifier (PIN-TIA) based receiver with a 35 GHz 3-dB electrical bandwidth. To aid the manual polarization alignment we added a marker tone into each polarization which was monitored using an electrical spectrum analyzer (ESA) that was connected to one of the two differential outputs of the PIN/TIA receiver. The resulting signal is digitized by a 160 GS/s analog to digital converter (ADC) and subsequently processed offline. The digital signal processing steps consists of: digital clock recovery and resampling to 1 Sa/symbol; feed-forward linear equalization (FFE) with 21 symbol-spaced taps and a single decision feedback equalizer (DFE) tap, optimized with least-means-square (LMS) metric; and bit error ratio (BER) counting.

4. Experimental Results

Fig. 2(b) shows BER versus optical power budget results measured with our 400G downstream PON setup. Assuming soft-input LDPC (sLDPC) forward error correction (FEC) with BER threshold=2×10^{-2}, we find a back-to-back optical power budget of >34.5 dB for all four channels. For both wavelengths, we find an optical path penalty (OPP) of up to ~1 dB after 20 km. For 1314 nm, we find an OPP of ~1 dB after 40 km and for 1320 nm we find an OPP of ~2.1 dB after 40 km. For hard-input LDPC (hLDPC) with BER threshold=1×10^{-2}, we find a back-to-back optical power budget of >32.5 dB for all four channels.

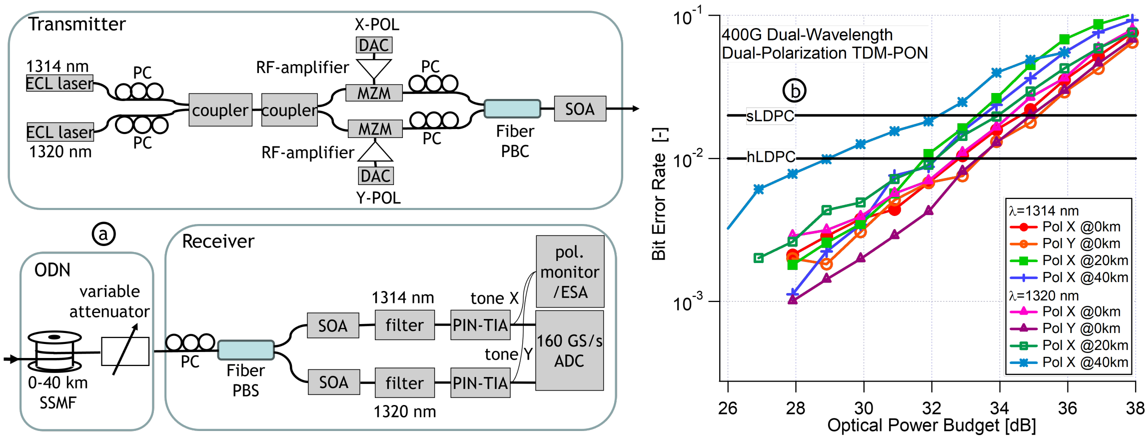

Fig. 2. Experimental setup to validate 400G DW-DP PON (a). Measured BER versus received optical power for the four channels for different fiber reaches (b).

The SOAs that were available in our lab have a polarization-dependent gain, so in our experimental setup we amplified each polarization separately at the receiver, which incurs a received sensitivity penalty of typically ~0.5 dB due to the insertion loss of the PBS. In a final system, polarization independent SOAs should be used to enable lowest complexity receiver architectures and most optimal receiver sensitivity. For bidirectional PON transmission, diplexer losses need to be considered, the combined diplexers and PBS losses will typically be <1.5 dB resulting in a >33 and >31 dB back-to-back power budget for sLDPC and hLDPC, respectively.

5. Discussion and Conclusion

We showed the feasibility of 400G dual-polarization and dual-wavelength IM-DD-based TDM-PON with >34.5 dB back-to-back power budget for sLDPC and >32.5 dB for hLDPC. After taking diplexer and PBS losses into account we achieved >3 dB optical margin in our setup to support a 29 dB power budget after 20 km fiber with sLDPC. After 40 km fiber at 1320 nm (equivalent to worst case total dispersion over 20 km at 1320 nm), the margin is still ~2 dB to achieve this power budget. In our setup the power budget was limited by the output power of the booster SOA. However, because our system uses ODB it is feasible to launch more optical power without the need to mitigate SBS penalties [3] to increase the optical power budget further.

The use of multiple channels offers opportunities to allow simplified ONU architectures. For a 400G PON, it will be feasible to lower the peak rate that an ONU can transmit or receive to below the maximum PON rate. For example, a 200G rate can be transmitted by using a single laser at the ONU transmitter, and similarly, an ONU can receive a 200G peak rate by receiving just one of the two wavelengths. Finally, even a 100G ONU transmitter based on a conventional electro absorption modulator-based transmitter (EML) modulated with 100G NRZ could be supported with our proposed PON architecture. Such reduced complexity ONU transceivers enable a cost-effective, scalable, and power consumption optimized very high speed PON.

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