First Demonstration of PAM4 Transmissions for Record Reach and High-capacity SWDM Links Over MMF Using 40G/100G PAM4 IC Chipset with Real-time DSP

Frank Chang[1], Yi Sun[2], Robert Lingle[2], You Zhang[1], Pengfei Cai[3], Mengyuan Huang[3], Dong Pan[3], Timo Gray[4], Sudeep Bhoja[1], Stephen Nelson[4], and Jim Tatum[4]
[1]Inphi Corp., 112 S. Lakeview Canyon Road, Suite 100, Westlake Village, CA 95054, USA,
[2]OFS Fitel LLC, 2000 Northeast Expressway, Norcross, GA 30071, USA
[3]SiFotonics Technologies, Woburn, MA 01801, USA
[4]Finisar Corp., Allen, TX, 75016, USA
fchang@inphi.com, ysun@ofsoptics.com

Abstract: We experimentally demonstrate, for the first time, link BERs under the KP4 FEC threshold at 42.5 Gbps over 550 m high bandwidth OM4 using single 850 nm VCSEL and at aggregated 212.5 Gbps over 300 m wideband multimode fiber using SWDM TOSAs from 850 to 940 nm, employing a newly developed PAM4 chipset and direct detection, with a novel Ge/Si APD or wideband PIN ROSA.

OCIS codes: (060.4510) Optical communications; (060.4080) Modulation; (250.3140) Integrated optoelectronic circuits

1. Introduction

VCSEL-based optical links operating at 850 nm over multimode fiber (MMF) still represent the vast majority (over 75%) of fiber deployments within data centers for low cost, low power consumption and short reach connectivity. Current 40 and 100G upgrades known as SR4 use four laser/detector pairs and 4 parallel fibers for transmitting and 4 parallel fibers for receiving at 10G or 25 Gbps per fiber. For most cases, optics usually take up main part of optical module cost. The optical PAM4 modulation (4-level pulse amplitude modulation) dramatically reduces optics counts by doubling the bits per symbol at the same baud rate. So far PAM4 signaling is the only viable non-NRZ signaling technology of choice for data center interconnects standards by various IEEE802.3 groups such as the 802.3cd 50/100/200 Gb/s Ethernet Task Force [1]. To allow transmission over duplex fibers with 10Gbps deployments, create building blocks for future 400 and 800 Gbps parallel modules, and maintain longer and extended reaches achievable at higher transmission rates, the combination of PAM4 signaling with short wavelength division multiplexing (SWDM) [2] and novel wideband MMFs (WBMMF) [3] are highly desirable. It's also useful to leverage recent advance in silicon photonics with the introduction of the Ge/Si APD [4] (avalanche photodiode) operating at ~25G range to address improved optical receiver sensitivity. A better receiver sensitivity potentially achievable with the low cost Ge/Si APD is useful for upgrades to higher data rates using current VCSEL and PAM4 CMOS technology, especially with the loss of receiver sensitivity inherent to PAM4 or insertion of optical MUX/DeMUX into the link for SWDM.

Prior measurements of PAM4 transmission at ~25 Gbaud or higher have either heavily relied on the offline post-processing techniques with the aid of expensive instruments [5-9] or to a much shorter reach on OM3/OM4 at 850 and 880 nm using PAM4 chip with real time BER function [10]. The longest reach on MMF was 300 m at 45 Gbps per wavelength using PAM4 chip [11]. To implement the PAM4 architecture with VCSEL lasers over transition from NRZ, the key IC building blocks, as shown in Fig. 1, include PAM4 DSP engine incorporating real-time DSP processing and FEC as well as high linearity, low power and high speed transimpedance amplifiers (TIA) and drivers.

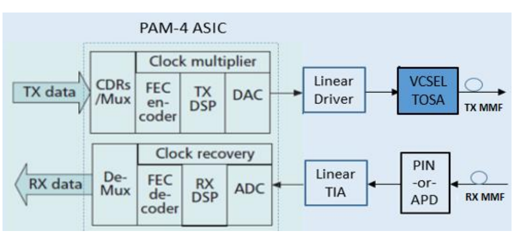

Fig. 1. Typical optical PAM4 transmitter and receiver IC MMF building blocks for optical modules like QSFP28.

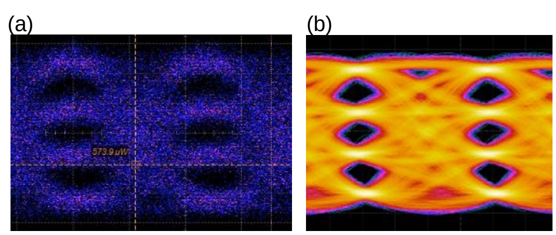

Fig. 2. a) 1λ 42.5Gbps PAM4 VCSEL optical eye; and b) subsequent PAM4 eye processed by linear equalizers.

In this paper, we applied the availability of industry's first 100G PAM4 IC chipset [12] operating error free under

KP4 FEC threshold at 21-26 Gbaud covering various scenarios for the case of MMFs: 1) Single 850 nm VCSEL (1λ) 42.5 Gbps transmission over extended MMF reach of the conventional OM4 including a high bandwidth OM4 of 8.8 GHz*km detected by conventional PIN and the novel Ge/Si APD; 2) dual channel (2λ) 53.125 Gbps transmission with multiplexed 850 and 880 nm or multiplexed 910 and 940 nm wavelengths over 300 m of WBMMF detected by wideband ROSA with linear TIA. This is the first time to apply the realized miniature PAM4 IC platform with newly developed Ge/Si APD for MMF links. We experimentally demonstrate the link operates error free under KP4 FEC threshold at single 850 nm VCSEL with 42.5 Gbps for record distance of 550 m OM4 and at SWDM wavelengths with aggregated 212.5 Gbps for 300 m of WBMMF.

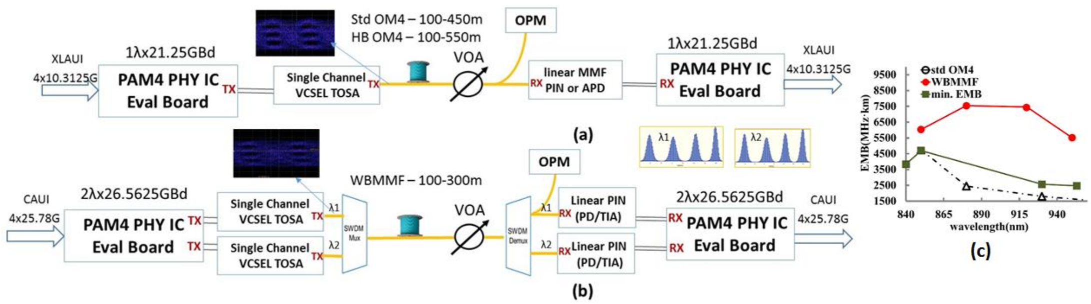

Fig. 3. PAM4 setup at (a) 1λ 40/50 Gbps VCSEL, (b) 2λ (or more) 100/200 Gbps VCSELs, with 850 nm TX optical eye diagram and RX DSP recovered histograms shown in inset; (c) shows the EMB vs. wavelength for conventional OM4 and WBMMF.

2. Experimental setups

The multi-purpose, 2-channel PAM4 PHY chip with real-time DSP capability is critical for generating the optical PAM4 signals. A block diagram of the DAC (digital-to-analog converter) based PAM4 PHY chip is shown in Fig. 1 and was described in details in Ref. 12. PAM4 transmitters leverage transmit (TX) DSP and DAC which maps the input MSB and LSB (most & least significant bits) streams into PAM4 symbols. Fig. 2(a) presents the electrical PAM4 eye directly from VCSEL, and (b) subsequent PAM4 optical eye diagram processed by linear equalizers.

The experimental PAM4 setups for 1λ x 42.5 and 2λ x 53.125 Gbps systems used in this work are depicted in Fig. 3(a) and (b) running at KP4 RS(544,514) FEC rates of 21.25 GBaud and 26.5625 GBaud, respectively. The multi-purpose 100G PAM4 PHY chip is the heart of the setup. In both experiments, the embedded PRBS generator and checker inside the chip facilitate the true real-time BER tests of the end-to-end optical PAM4 link. We used the worst-case PRBS 2^{31}-1 pattern throughout this work to emulate the real data traffic.

The 2λ x 53.125 Gbps experimental setup is similar to that of 1λ PAM4 (Fig. 3), but with two of the four SWDM4 wavelengths (850 and 880 nm, or 910 and 940 nm) each running simultaneously at 53.125 Gbps. Two wavelengths are optically multiplexed after TOSAs and de-multiplexed before ROSA using two out of four ports of a packaged NETWORK Cube Multimode CWDM-MUX-4 Module from Huber+Suhner.

For fiber spools, we used two OM4 samples including an off-the-shelf OM4 fiber passing specification of minimum effective modal bandwidth (EMB) of 4.7 GHz*km (shown as green square in Fig. 3(c)) and an OM4 with higher EMB of 8.8 GHz*km at 850 nm. A next generation WBMMF (NG-WBMMF) with EMB over 6 GHz*km (shown in red in Fig. 3(c)) was used for 2λ x 53.125 Gbps experiments.

At the receive side, we investigated the novel Ge/Si APD ROSAs with same linear TIA (IN2860TA) as for the reference PIN for potential low cost. The high speed TIA incorporates AGC function (automatic gain control) to maintain high linearity.

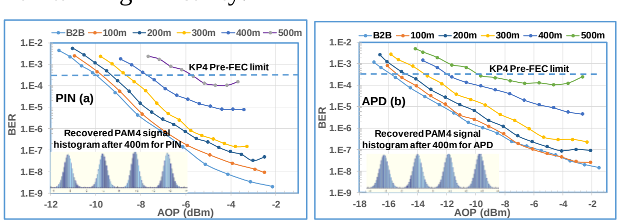

Fig. 4. BER vs. RX optical power plots with PIN (a) and APD (b) for standard **OM4** transmission for VCSEL at 850 nm.

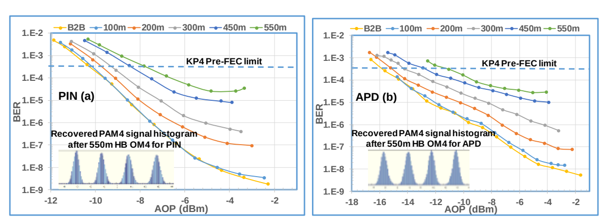

Fig. 5. BER vs. RX power plots with PIN (a) and APD (b) for high bandwidth **OM4** transmission for VCSEL at 850 nm.

3. 1λ 40G transmission over 550m OM4

The system performance was quantified with measurements of BER versus (vs.) average received (Rx) optical power (AOP). The results with PIN and APD over various distances are illustrated in Fig. 4 and Fig. 5 for the two OM4 MMFs. The maximum practical distance over the off-the-shelf OM4 can be achieved to be over 400 m for one order of magnitude lower BER than KP4 FEC limit at 2.4 x 10^{-4}, while such distance is extended to 550m for the high bandwidth OM4. There is error floor for 450m or 500m distance due to modal dispersion. The APD shows -15.9 dBm sensitivity at B2B, which is ~4.8 dB better over PIN. The improvement is done by optimizing electronic equalizers embedded with the PAM4 chip. The power penalties at pre-FEC BER threshold increase dramatically with distance, while for the 100m case it is almost negligible (<0.2 dB) as compared to B2B case. The link was tested to run error free for the PIN case above sensitivity when the FEC is enabled with full Ethernet traffic.

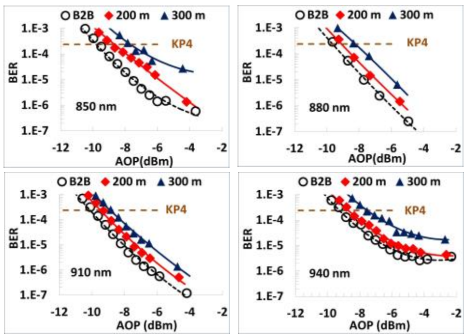

Fig. 6. BER vs. RX optical power with PIN for **WBMMF** at SWDM wavelengths from 850nm to 940nm.

Table 1. Link budget, total peanlties, DPP and attenuation for 200 and 300 m at four SWDM wavelengths

λ_c (nm)	Link budget (dB)	Total penalty (dB)		DPP (dB)		Attenuation (dB)		
		200 m	300 m	200 m	300 m	200 m	300 m	MUX / DeMUX
853	7.9	3.5	4.7	1.1	2.1	2.3	2.6	1.8
881	7.1	3.4	4.4	0.6	1.4	2.9	3.0	2.3
911	7.7	2.6	3.3	0.3	0.9	2.3	2.4	1.8
941	8.8	3.2	4.4	1.1	2.3	2.1	2.2	1.8

4. 2-λ 100/200Gbps 300m transmission

Fig. 6 depicts the BER vs. AOP curves running at 53.125 Gbps for B2B, 200 and 300m at the SWDM4 wavelengths of 850, 880, 910, and 940 nm, respectively. The link budget (difference between Tx optical power and B2B receiver sensitivity), total penalties including attenuation, dispersion power penalty (DPP) and attenuation at BER=2.4 x 10^{-4} for 200 and 300 m of NG-WBMMF at SWDM4 wavelengths are summarized in Table 1. The maximum DPP is 2.3 dB and attenuation is 3.0 dB where 2.3 dB is attributed to each MUX/DeMUX pair. The total penalty is 4.7 dB at maximum for 300 m distance, allowing 2.7 to 4.4 dB margin from 850 to 940 nm.

5. Conclusions

By leveraging the newly developed PAM4 IC chipset, link performance with real-time DSP in miniaturized silicon format was extensively studied for standard OM4 and WBMMF for upgrades to 40/50 and 100/200 Gbps. This is the first known experimental data in this wavelength region to report the PAM4 transmission for record reach of 550 m with the Ge/Si APD and record aggregated rate of 212.5 Gbps over WBMMF with real-time DSP processing. The results demonstrate 550 m transmission at 850 nm for OM4 and 300 m across 4 SWDM wavelengths over WBMMF with MUX/DeMUX included. The availability of complete IC platform enables small form factor modules such as QSFP28 for the wide deployments in data centers.

Acknowledgements

The authors would like to acknowledge Loi Nguyen, Ricky Chen, Lian Zhao, Frank Gelhausen, Kristine Scott and Alan McCurdy for support and contribution.

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