HOM Papers from OFC 2015 Potentially Addressing BTI

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SMF Adhoc

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List of relevant papers

- Single Channel 112 Gbit/s PAM4 at 56 Gbaud with Digital Signal Processing for Data Centers Applications
- Practical Implementation of 100-Gbit/s/Lambda Optical Short-Reach Transceiver with Nyquist PAM4 Signaling using Electroabsorptive Modulated Laser (EML)
- Transmission of 56-Gb/s PAM-4 over 26-km Single Mode Fiber Using Maximum Likelihood Sequence Estimation
- 112 Gb/s PAM4 Transmission Over 40 km SSMF Using 1.3 um Gain-Clamped Semiconductor Optical Amplifier
- Experimental Demonstration of 500 Gbit/s Short Reach Transmission Employing PAM4 Signal and Direct Detection with 25Gbps Device
- High-linearity Avalanche Photodiode for 40-km Transmission with 28-Gbaud PAM4
- 130-Gbps DMT Transmission using Silicon Mach-Zehnder Modulator with Chirp Control at 1.55-um
- Four-Channel 100 Gb/s per Channel Discrete Multi-Tone Modulation Using Silicon Photonics Integrated Circuits
- 25GBaud PAM-4 Error Free Transmission over both Single Mode Fiber and Multimode Fiber in a QSFP form factor based on Silicon Photonics.

Single Channel 112 Gbit/s PAM4 at 56 Gbaud with Digital Signal Processing for Data Centers Applications

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- **Dan Sadot et. al. Multiphy, OFC 2015, Th2A.67**
  - Result similar to what has already presented to IEEE802.3bs with MSLE receiver

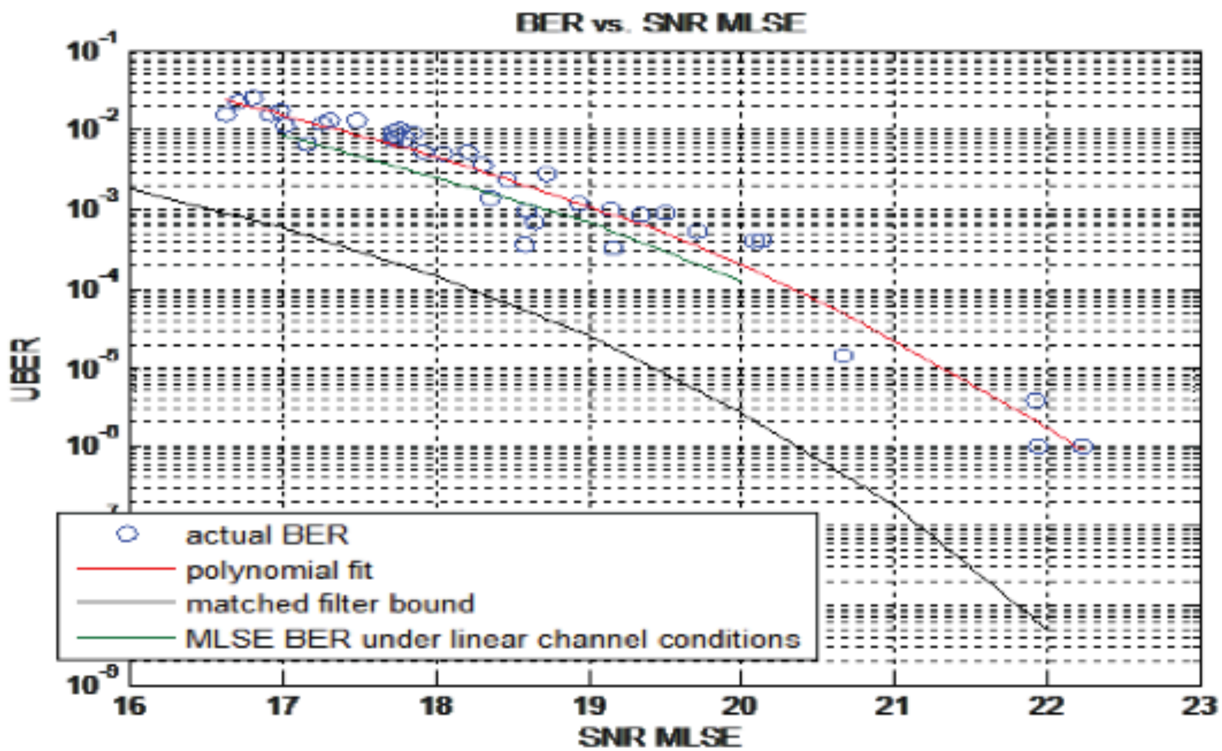

Figure 3. Comparison between measured and theoretical BER

Practical Implementation of 100-Gbit/s/Lambda Optical Short-Reach Transceiver with Nyquist PAM4 Signaling using Electroabsorptive Modulated Laser (EML)

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- **Nobuhiko Kikuchi et. al. Hitachi, OFC 2015, Th3A.2**
  - Result similar to what has already presented to IEEE802.3bs
  - Sensitivity is estimated by assuming 1 error/symbol to be -8.5 dBm @1300 nm at BER 2E-3 but no result to show absent of error floor.

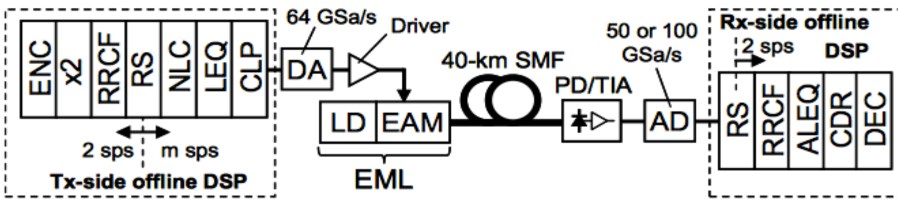


Fig. 1 Experimental setup of IM/DD Nyquist-PAM4 transceiver. ENC: PAM4 encoder, x2: twice up-sampling, RRCF: root-raised-Cosine filter, RS: re-sampling, NLC: modulator non-linear compensator, LEQ: linear equalizer, CLP: Clipping, DA: DA converter, LD: laser diode, EAM: Electro-absorption modulator, AD: AD converter (50 and 100 GSa/s for 42.67 and 51.2 GBaud, respectively), ALEQ: adaptive LEQ, CDR: clock and data recovery, DEC: PAM4 decoder.

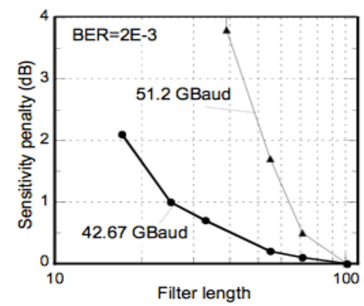


Fig. 2 Equalizing filter length against receiver sensitivity penalty.

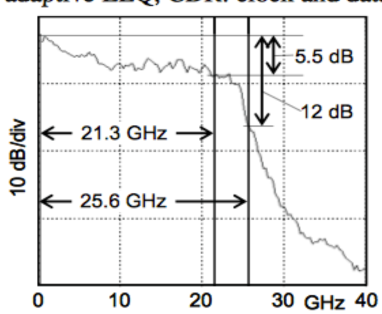


Fig. 3 Received Nyquist PAM4 signal spectrum without linear equalization.

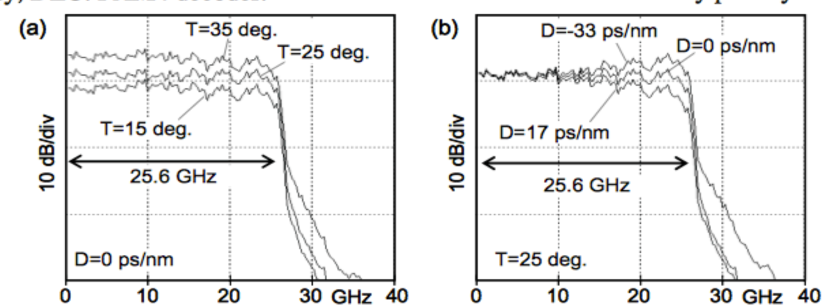


Fig. 4 Experimentally received spectra of 102.4-Gbit/s Nyquist PAM4 signal of 1.5-µm EML with the effect of (a) EML Temperature (T) and (b) Chromatic dispersion (D), both with the same received power.

Transmission of 56-Gb/s PAM-4 over 26-km Single Mode Fiber Using Maximum Likelihood Sequence Estimation

❑ Chen Chen et. al., Huawei, OFC 2015 TH4A.5

- Show feasibility of 50 and 100 Gb/s PAM4 with MLSE and PD-LUT (non-linear decision)
- 112 Gb/s PAM4 show persistent error floor similar to what we have seen in IEEE.

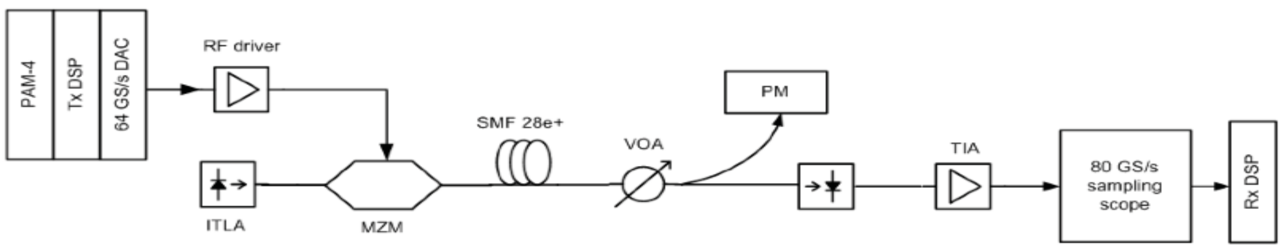


Fig. 1: Experimental setup. PM: power meter. ITLA: integrated tunable laser

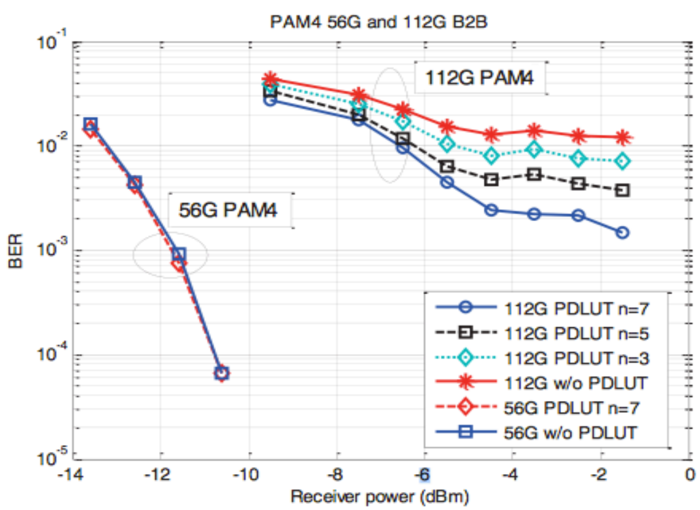


Fig. 3: 56-Gb/s and 112-Gb/s PAM-4 B2B result using PD-LUT.

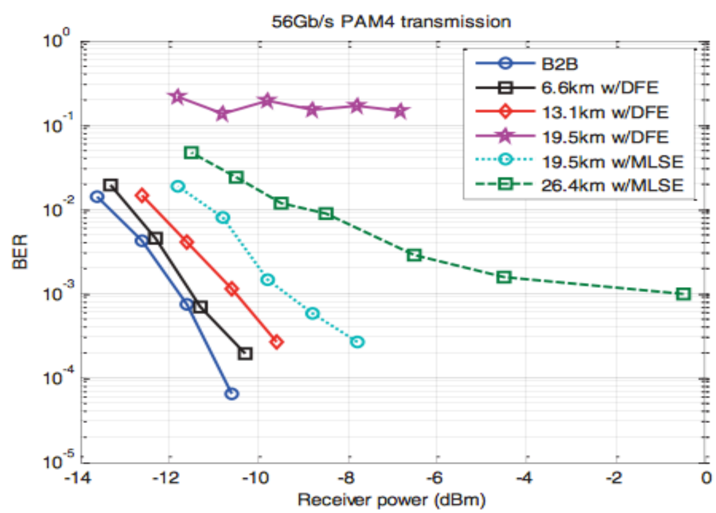


Fig. 4: 56-Gb/s PAM-4 transmission result.

112 Gb/s PAM4 Transmission Over 40 km SSMF Using 1.3 um Gain-Clamped Semiconductor Optical Amplifier

- **Trevor Chan and Winston Way, NeoPhotonics, OFC 2015 TH3A.4**
  - Result similar to what Trevor and Winston have presented in IEEE error floor persistent in case of 112 Gb/s PAM4 even with SOA front end.

The experimental setup for 2×56 and 1×112 Gb/s PAM4 systems are shown in Fig. 1(a) and Fig.1(b), respectively.

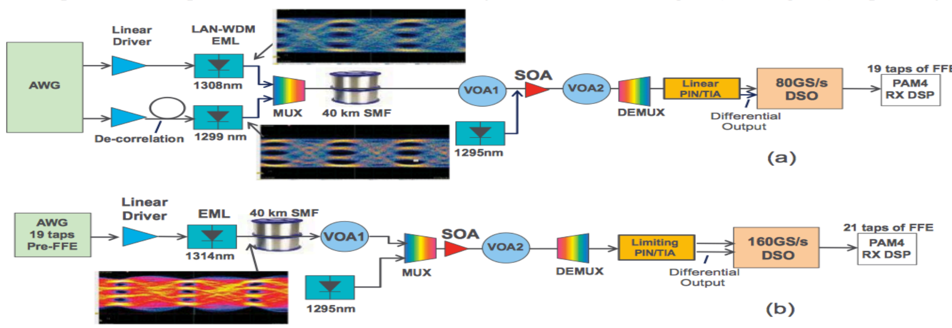


Fig.1 Experimental setup: (a) 2×56Gb/s PAM4 and (b) 1×112Gb/s PAM4, both with a clamp at 1295nm. Optical eyes are shown in the insets.

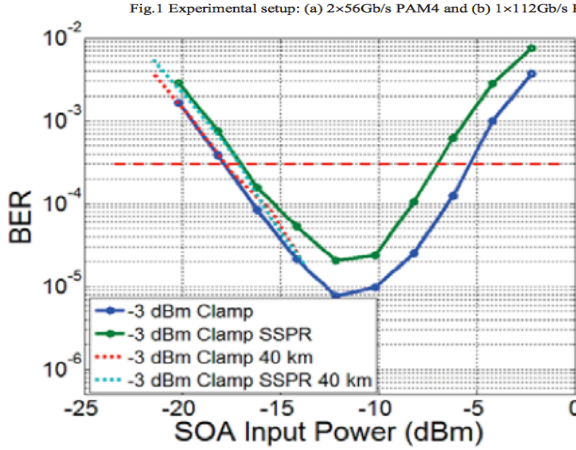


Fig.4 2×56Gb/s PAM4 BER vs SOA input power for 40km SSMF transmission at 1308nm, with -3dBm clamp power, and using either PRBS15 or SSPR test pattern.

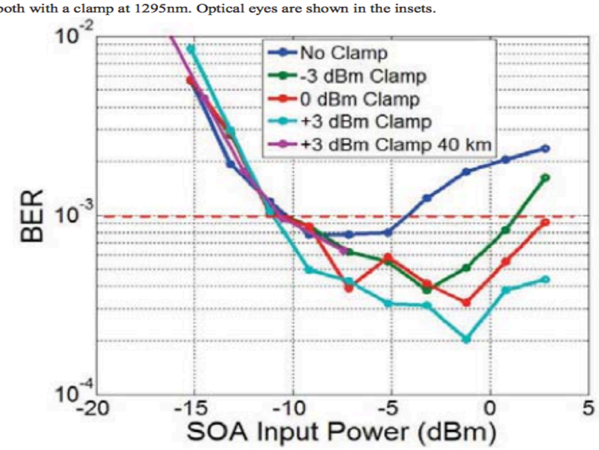
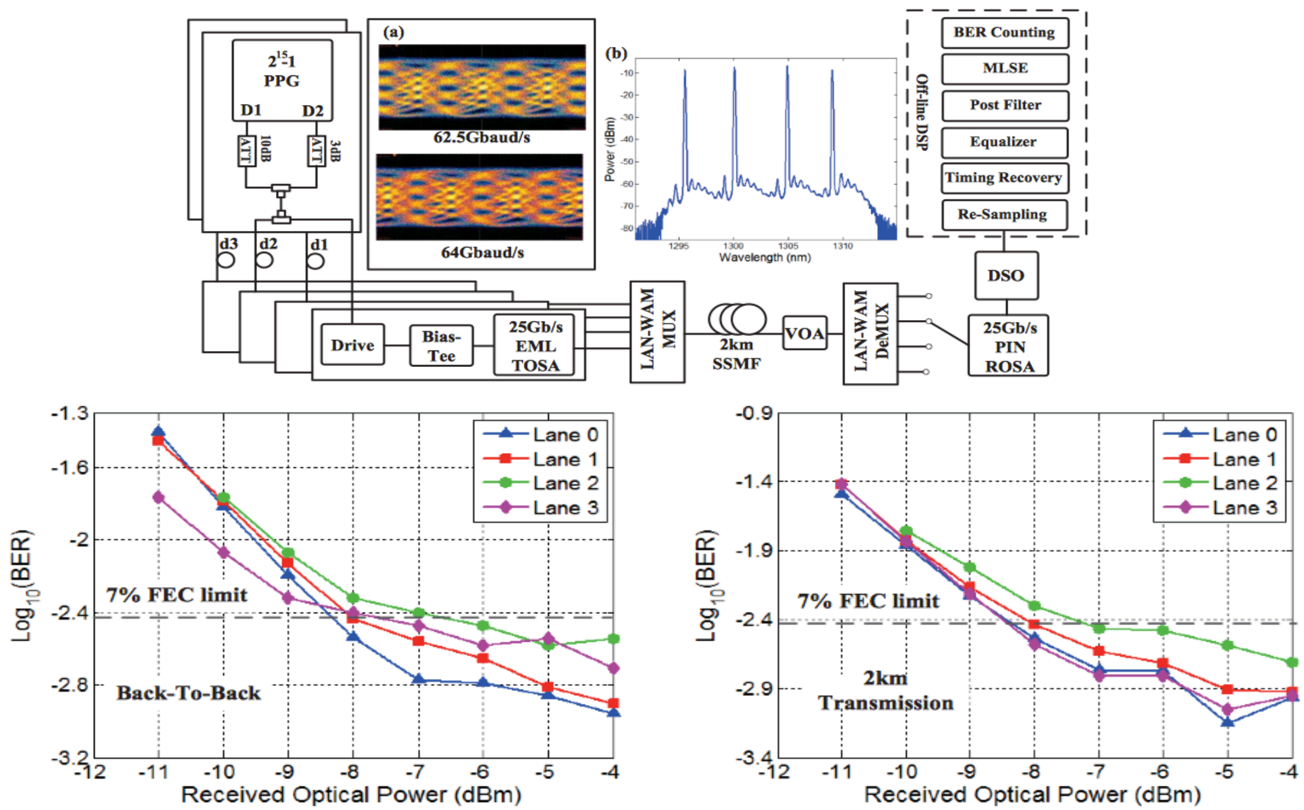


Fig.5 1×112Gb/s PAM4 BER vesus SOA input power for 1314nm, with and without gain clamps. 40km transmission result is shown for +3dBm clamp power.

SOA Gain ~12 dB
For 0 dBm Clamp

Experimental Demonstration of 500 Gbit/s Short Reach Transmission Employing PAM4 Signal and Direct Detection with 25Gbps Device

- **Kangping Zhong et. al. (Jiangwei Man Huawei LTD) , Hong Kong Polytechnic, OFC 2015, TH3A.3**
  - 128 Gb/s PAM 4 demonstrated with 7% FEC (3.8e-3) off line processing with MLSE
  - The classic error floor seen IEEE802.3bs with 100 Gb/s link also exist in this paper.



ig. 3: Measured bit error rate as a function of received optical power for 500Gbit/s system: (a) back-to-back system. (b) 2km transmission.

High-linearity Avalanche Photodiode for 40-km Transmission with 28-Gbaud PAM4

- **Masahiro Nada et. al., NTT, OFC 2015, M3C.2**
  - Highly linear APD achieved a BER of 2.3e-4 achieved at -17.0 dBm
  - APD has BW of 21 GHz with gain of 10 dB
    - APD had 2 dB compression at ~-3 dBm
    - According to Nada-san a device with 30 GHz BW and gain of 4.5 is in the feasibility stage expected commercialization date by 2018 or later
  - APD supply 27 V
  - Receive sensitivity is in AOP, ER/OMA unknown due to test equipment limitation

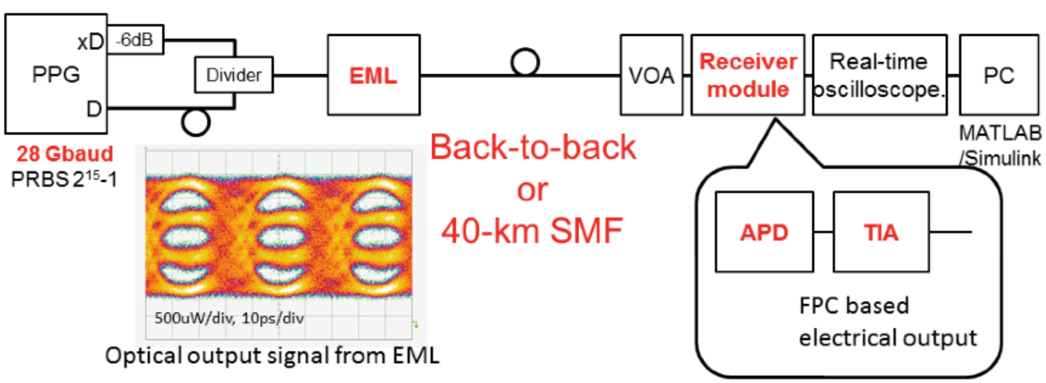
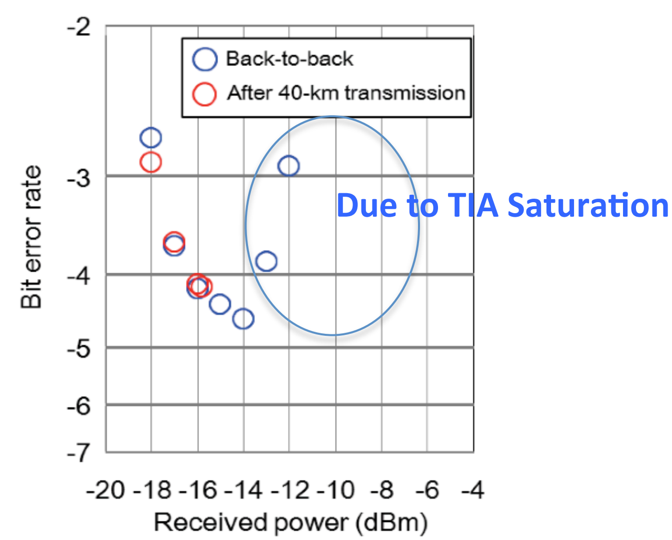


Fig. 3. Measurement setup of 28-Gbaud PAM4 40-km transmission BER test.



. 4. BER characteristics of fabricated APD receiver module at back-to-back and after 40-km transmission.

130-Gbps DMT Transmission using Silicon Mach-Zehnder Modulator with Chirp Control at 1.55-um

- **Yutaka Kai et. al., Fujitsu LTD, OFC 2015, Th4A.1**
  – At KP4 FEC limit the 10 km link without Mux/de-mux has capacity of ~80 Gb/s
  – At KP4 FEC limit demonstrate feasibility 100 Gb/s 2 km PSM4

Table 1. Specification of the silicon MZM

Parameter	Values
Wavelength	1530-1620 nm
Insertion loss	10.2 dB
Vπ	7.8 V
Driver amp.	6.5 V
Extinction ratio (Static)	26.73 dB
Bandwidth	12.5 GHz

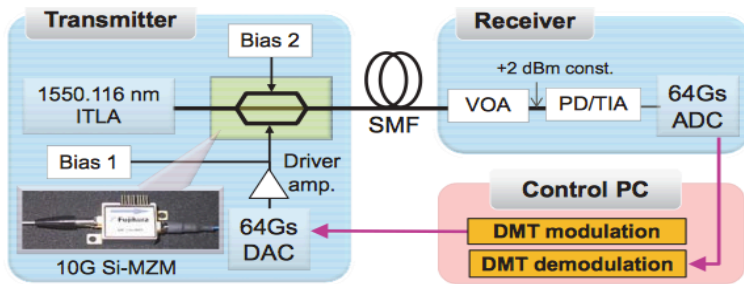
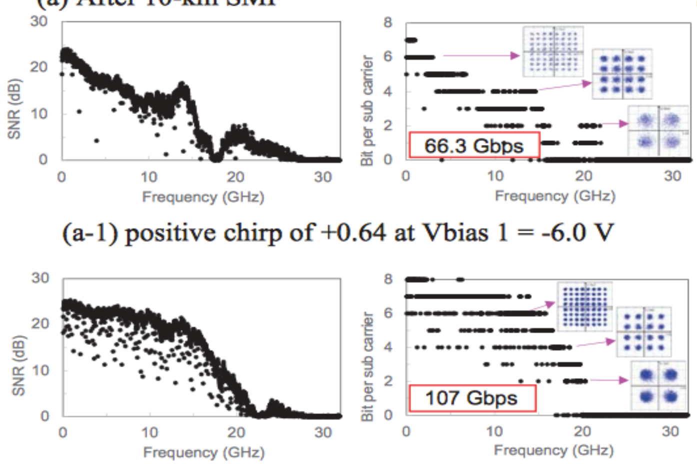


Figure 2. Experimental setup of SMF 10 km transmission at 1550-nm band and photograph of the 10G silicon MZM package

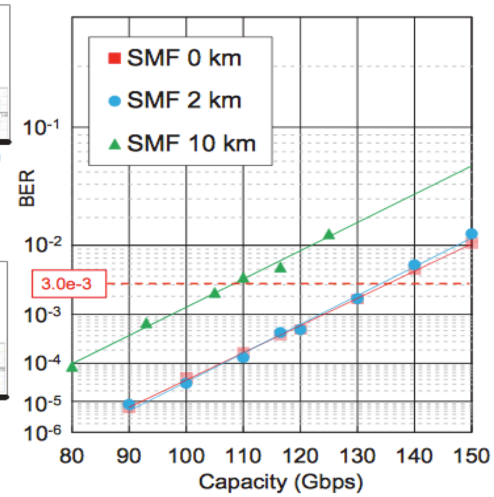
(a) After 10-km SMF



(a-1) positive chirp of +0.64 at Vbias 1 = -6.0 V

(a-2) negative chirp of -0.72 at Vbias 1 = -10.5 V

(b) BER characteristics



Four-Channel 100 Gb/s per Channel Discrete Multi-Tone Modulation Using Silicon Photonics Integrated Circuits

- **Po Dong et. al. Bell Lab, OFC 2015 Post Deadline, TH5B.4**
  - At our FEC limit of 2.5e-4 only ~55 Gb/s supported through the channel!

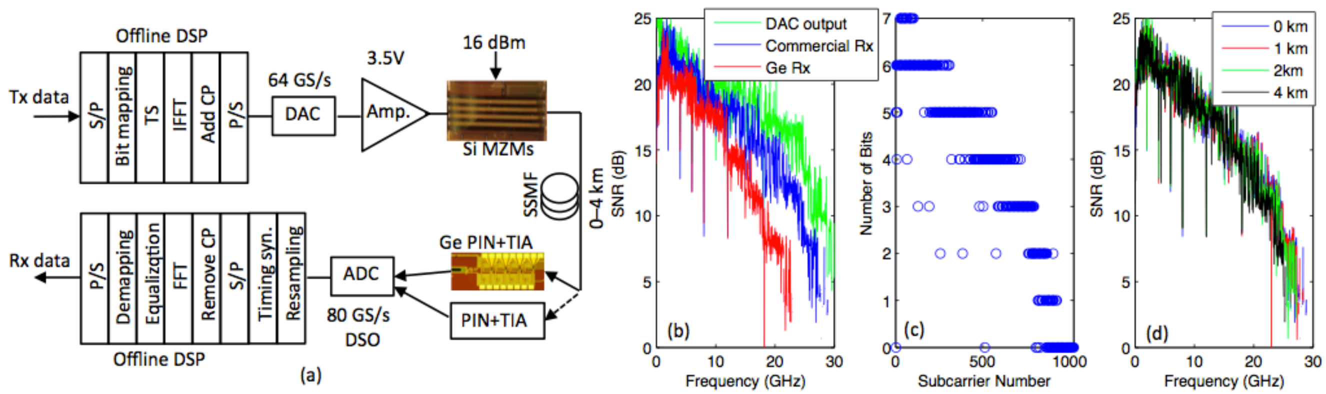


Fig. 2: (a) Experimental setup for DMT modulation, transmission and detection. (b) Measured SNRs per carrier. (c) Bit allocation per subcarrier after bit loading. (d) SNRs for different transmission lengths.

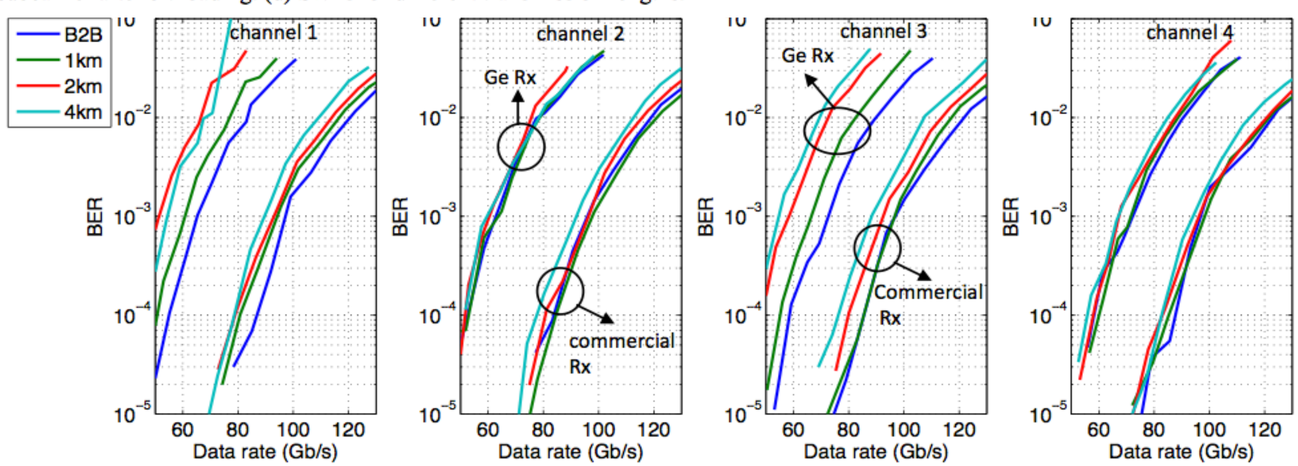


Fig. 3: BERs for four channels and different transmission distance. The group of higher data rates are for commercial receiver, while the others are for silicon-PIC receiver. When silicon-PIC receiver is used, channel *i* stands for the link from the MZM *i* to the Ge PD *i*.

25GBaud PAM-4 Error Free Transmission over both Single Mode Fiber and Multimode Fiber in a QSFP form factor based on Silicon Photonics

- **M. Mazzini et. al., Cisco, OFC Post Deadline, TH5B.3**
  - At 25.6 GBaud error floor of better 1E-8 demonstrated
  - At 25.6 GBaud Achieves $OMA_{00\text{-}03}$ sensitivity of -11 dBm at ~1E-4

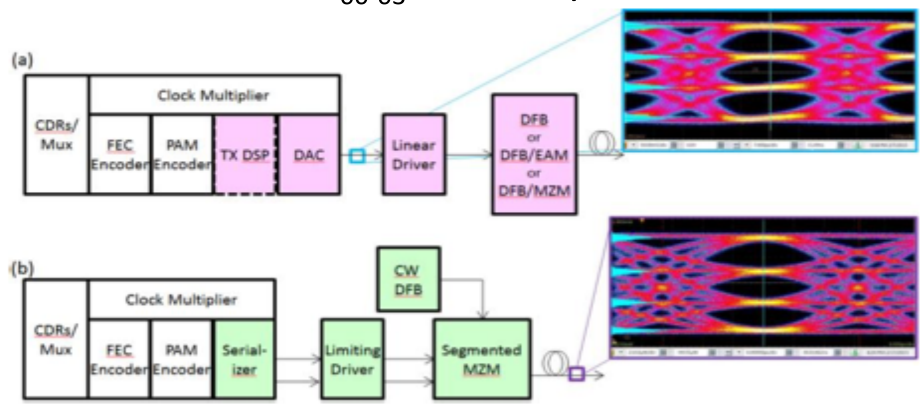


Fig.1: (a) DAC based PAM-4 transmitter block diagram with BCM82040 25Gbaud PAM-4 electrical eye, and (b) Segmented MZI PAM-4 transmitter block diagram with Cisco PAM-4 optical eye diagrams.

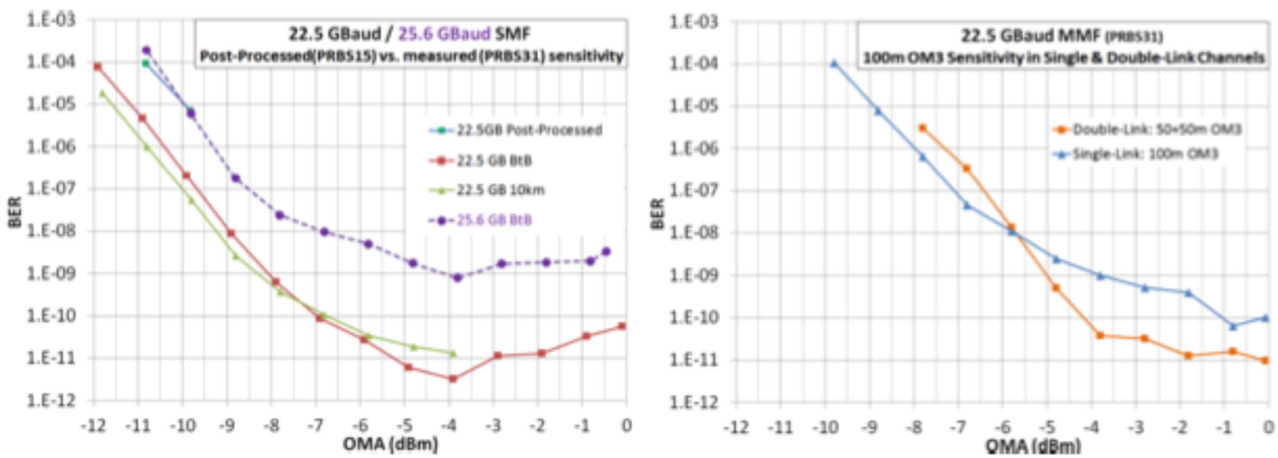
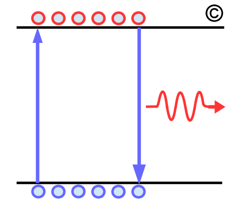


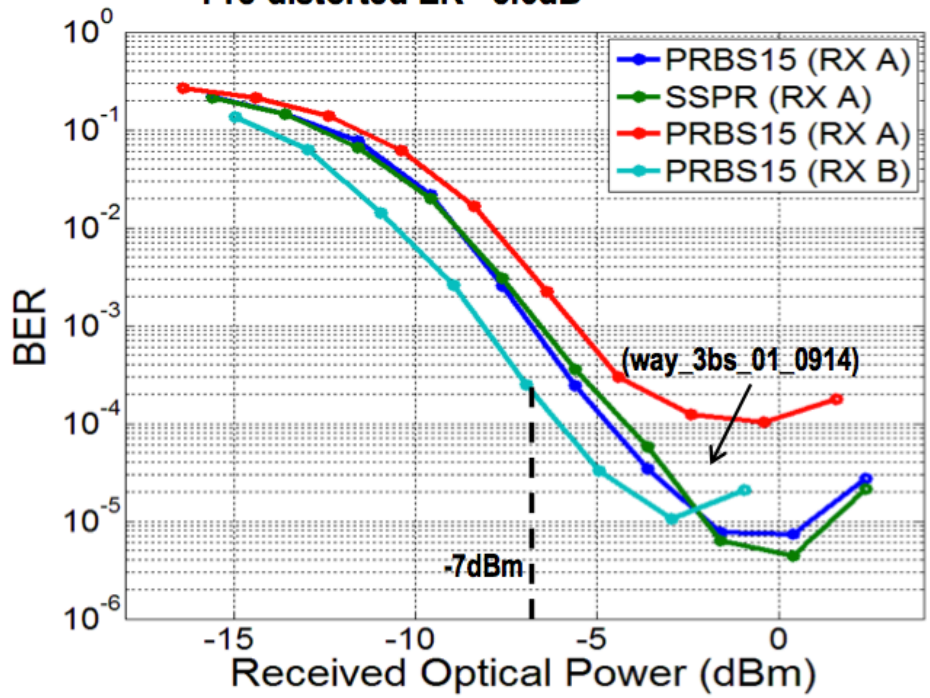
Fig.3: PAM-4 Sensitivity: (a) BtB and 10km SMF at 22.5GBaud and BtB at 25.6GBaud; (b) Single and double-link MMF at 22.5 GBaud.

way_3bs_01a_0115.pdf in 802.3bs are the best 100G results reported



112Gb/s PAM4 Experimental Results

Low-end cutoff frequency <50KHz
Pre-distorted ER= 5.6dB



	RX A	RX B
Responsivity (A/W)	0.4	0.7
3dB BW (GHz)	40	30
Spectral noise density (pA/√Hz)	40	35

2~3 times BER improvement can be done by further equalizing the three inner eye amplitudes

NeoPhotonics

Summary

- **Many of us had high hope that we will see some breakthrough results in regard to 100 Gb/s/lane HOM at OFC actually in IEEE we have seen updated results from**
  - MultiPhy - MLSE
  - Hitachi - Nyquist signaling
  - NeoPhotonics – 50/100G PAM4
  - Fujitsu – DMT
- **Two distinct papers can address 50 Gb/s PAM4 BTI**
  - NTT- Highly linear 28 GBd APD
    - Could address HOM link budget for higher loss and/or reach
  - Cisco – 28 GBd PAM4
    - Showing feasibility of 10 km reach 100G-LR2
- **OFC 2015 does not address our current 100 Gb/s BTIs**
  - Longer term potentially 28 GBd APD could provide sufficient gain-bandwidth product for 100 Gb/s.