

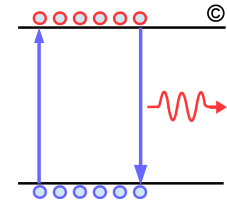
# HOM Papers from OFC 2015 Potentially Addressing BTI

**Ali Ghiasi**  
**Ghiasi Quantum LLC**

**SMF Adhoc**

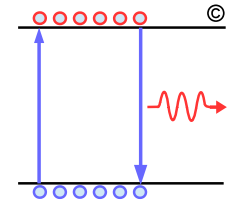
**April 28, 2015**

# 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



## □ Dan Sadot et. al. **Multiphy**, OFC 2015, Th2A.67

- Result similar to what has already presented to IEEE802.3bs with MSLE receiver

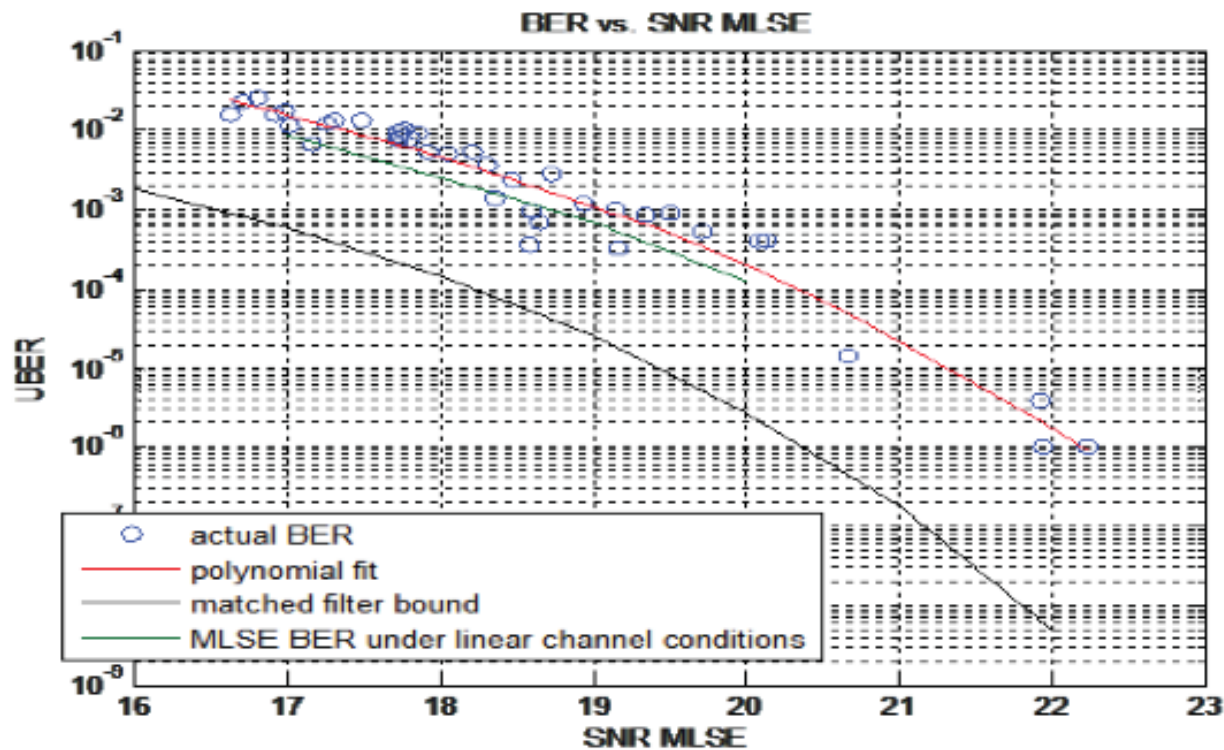
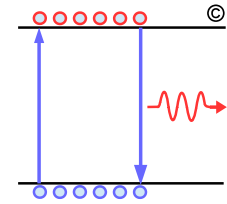


Figure 3. Comparison between measured and theoretical BER

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



## □ 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.

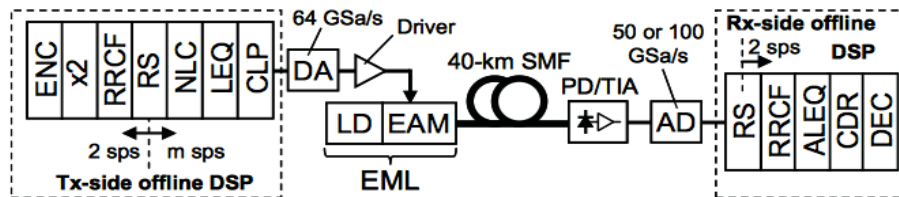


Fig. 1 Experimental setup of IM/DD Nyquist-PAM4 transceiver. ENC: PAM4 encoder, x2: twice up-sampling, RRCF: root-raised-Cosine filter, RS: re-sampling, NLC: modulator non-linear compensator, LEQ: linear equalizer, CLP: Clipping, DA: DA converter, LD: laser diode, EAM: Electro-absorption modulator, AD: 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.

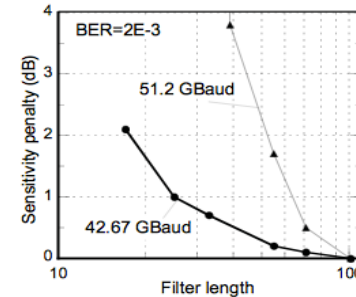


Fig. 2 Equalizing filter length against receiver sensitivity penalty.

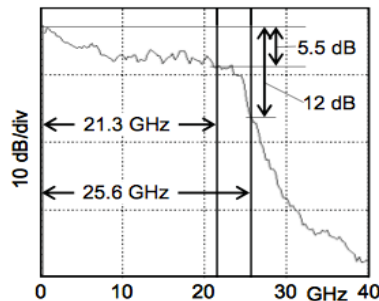


Fig. 3 Received Nyquist PAM4 signal spectrum without linear equalization.

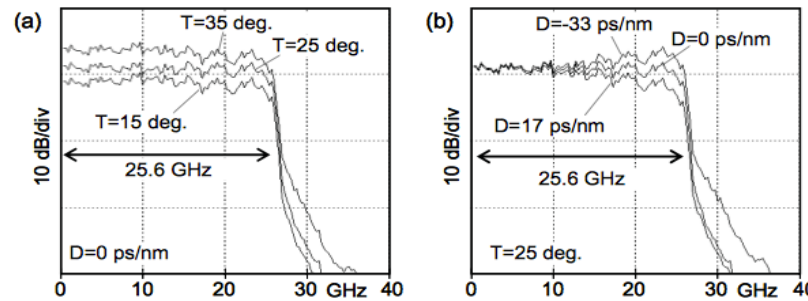
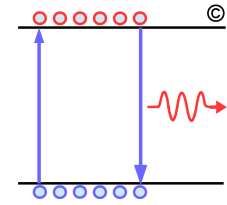


Fig. 4 Experimentally received spectra of 102.4-Gbit/s Nyquist PAM4 signal of 1.5- $\mu$ m EML with the effect of (a) EML Temperature (T) and (b) Chromatic dispersion (D), both with the same received power.

# 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.

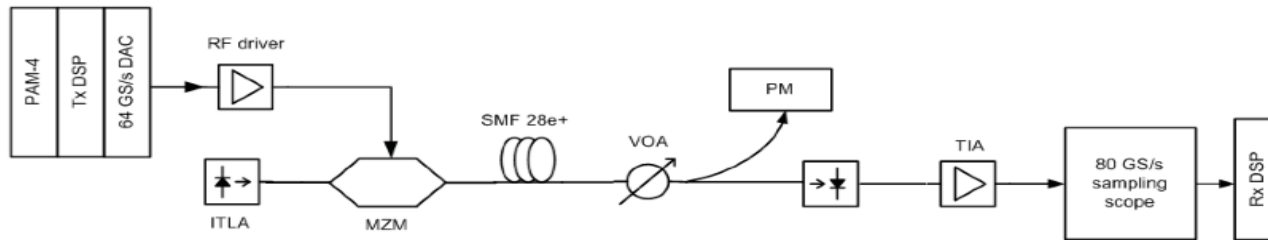


Fig. 1: Experimental setup. PM: power meter. ITLA: integrated tunable laser

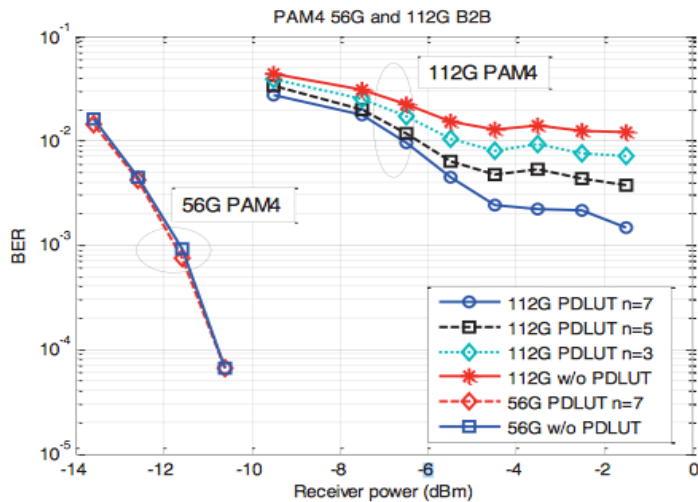


Fig. 3: 56-Gb/s and 112-Gb/s PAM-4 B2B result using PD-LUT.

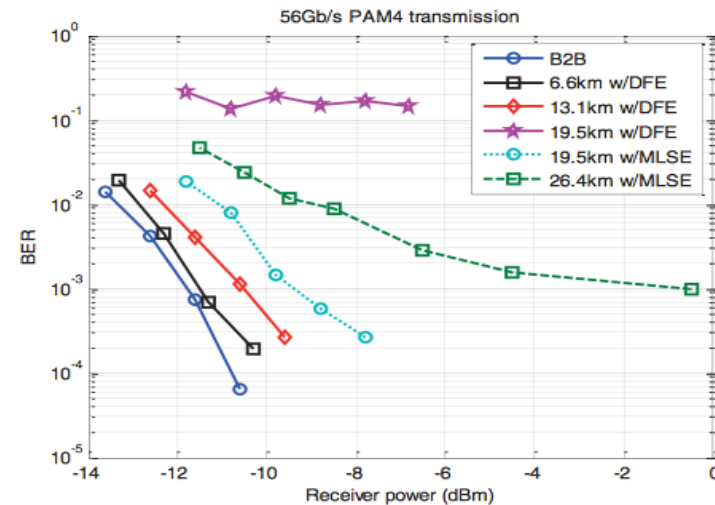
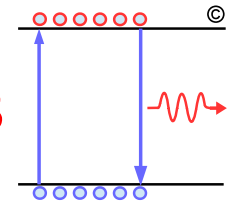


Fig. 4: 56-Gb/s PAM-4 transmission result.

# 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 2x56 and 1x112 Gb/s PAM4 systems are shown in Fig. 1(a) and Fig.1(b), respectively.

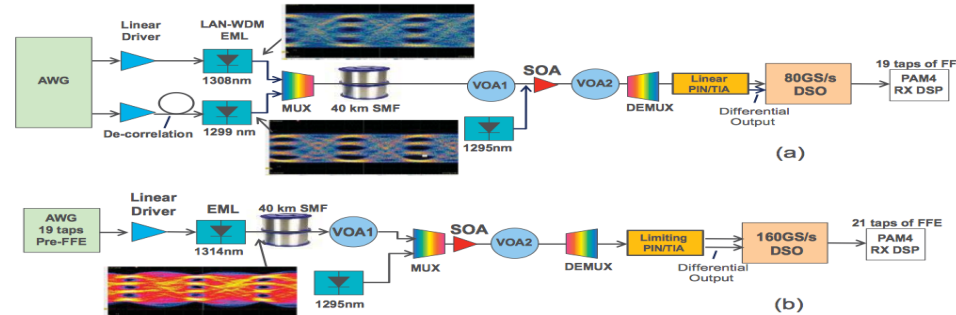


Fig.1 Experimental setup: (a) 2x56Gb/s PAM4 and (b) 1x112Gb/s PAM4, both with a clamp at 1295nm. Optical eyes are shown in the insets.

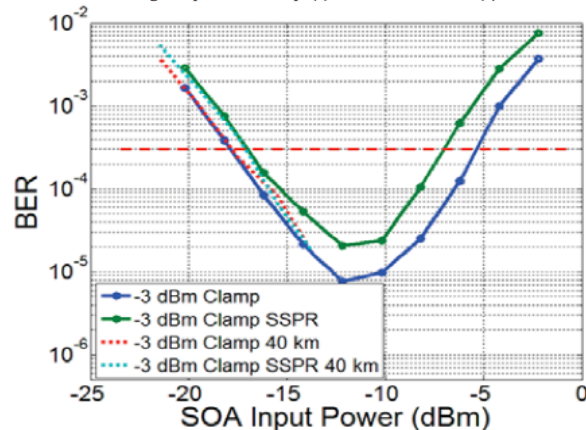


Fig.4 2x56Gb/s PAM4 BER vs SOA input power for 40km SSMF transmission at 1308nm, with -3dBm clamp power, and using either PRBS15 or SSPR test pattern.

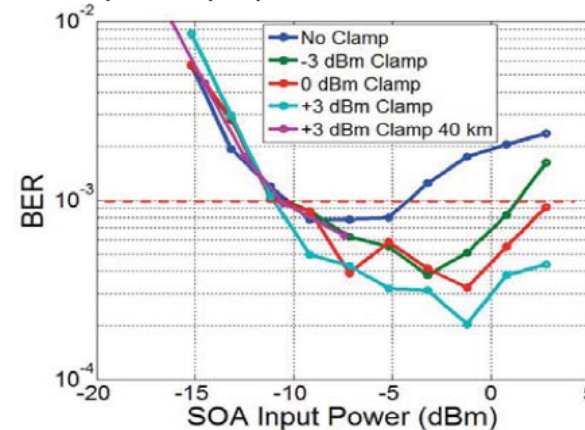
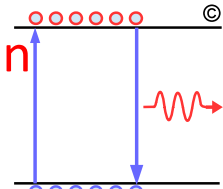


Fig.5 1x112Gb/s PAM4 BER versus SOA input power for 1314nm, with and without gain clamps. 40km transmission result is shown for +3dBm clamp power.

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.

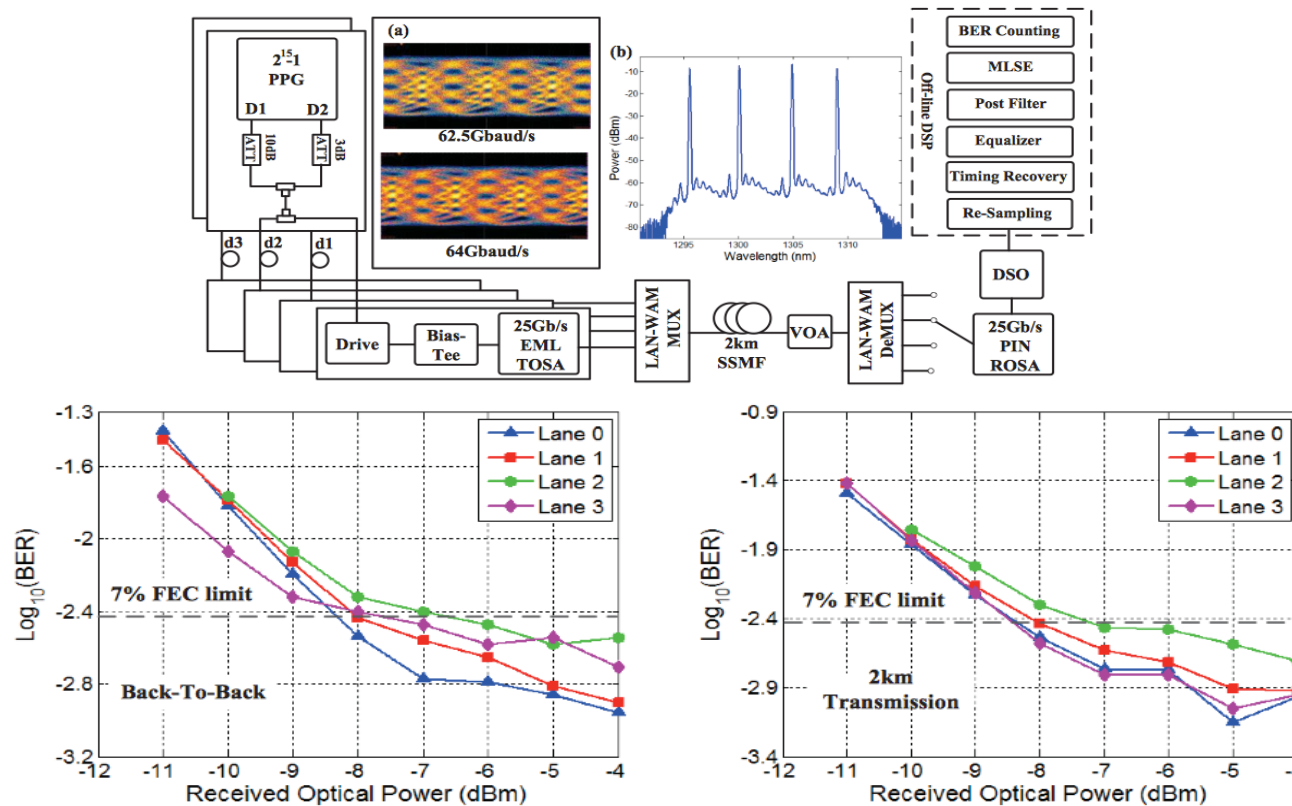
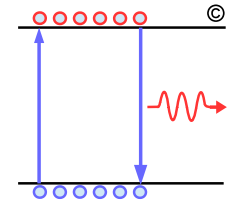


fig. 3: Measured bit error rate as a function of received optical power for 500Gbit/s system: (a) back-to-back system. (b) 2km transmission. SMF Adhoc

# 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  $2.3 \times 10^{-4}$  achieved at -17.0 dBm
- APD has BW of 21 GHz with gain of 10 dB
  - APD had 2 dB compression at  $\sim -3$  dBm
  - According to Nada-san achieving 30 GHz BW with gain of 10 is not feasible with current technology
- APD supply 27 dB
- Receive sensitivity is in AOP, ER/OMA unknown due to test equipment limitation

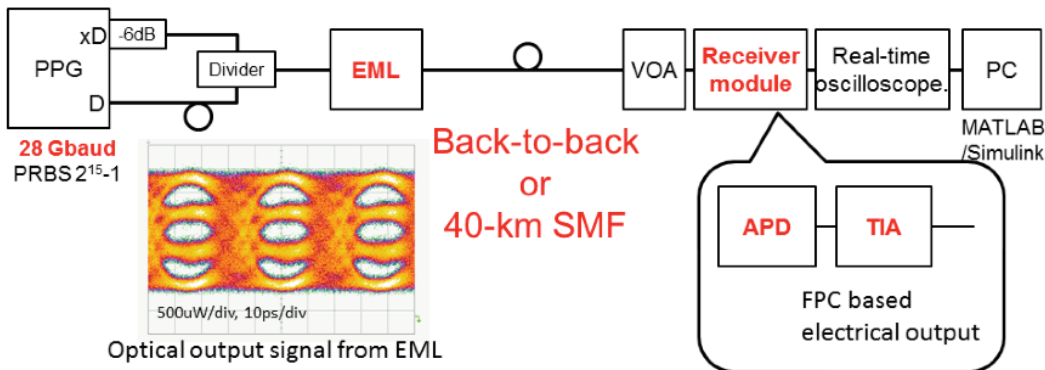
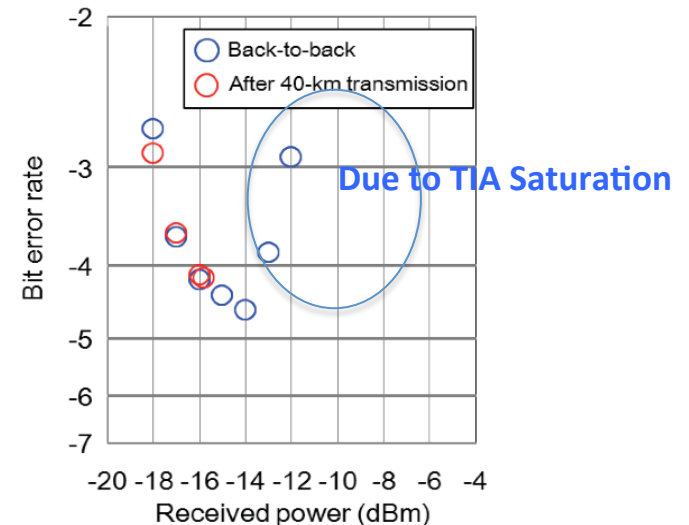


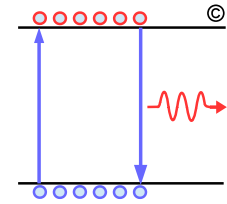
Fig. 3. Measurement setup of 28-Gbaud PAM4 40-km transmission BER test.



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  $\sim 80$  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
$V_{\pi}$	7.8 V
Driver amp.	6.5 V
Extinction ratio (Static)	26.73 dB
Bandwidth	12.5 GHz

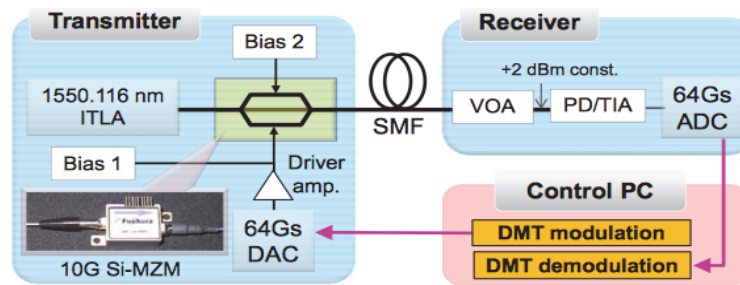
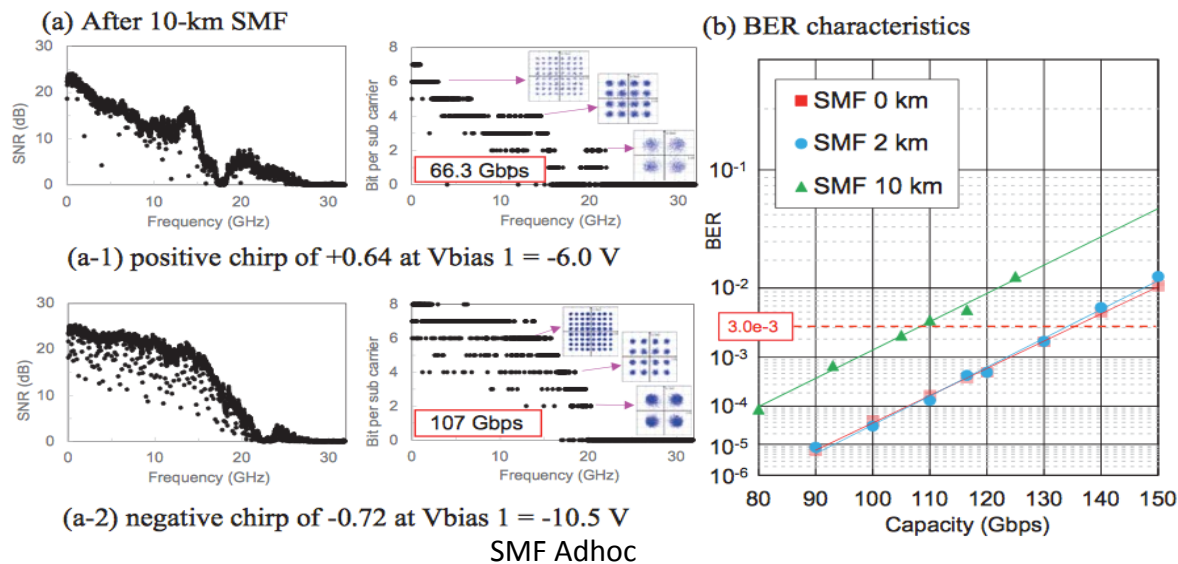
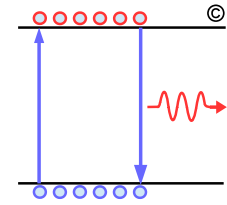


Figure 2. Experimental setup of SMF 10 km transmission at 1550-nm band and photograph of the 10G silicon MZM package



# 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  $\sim 55$  Gb/s supported through the channel!

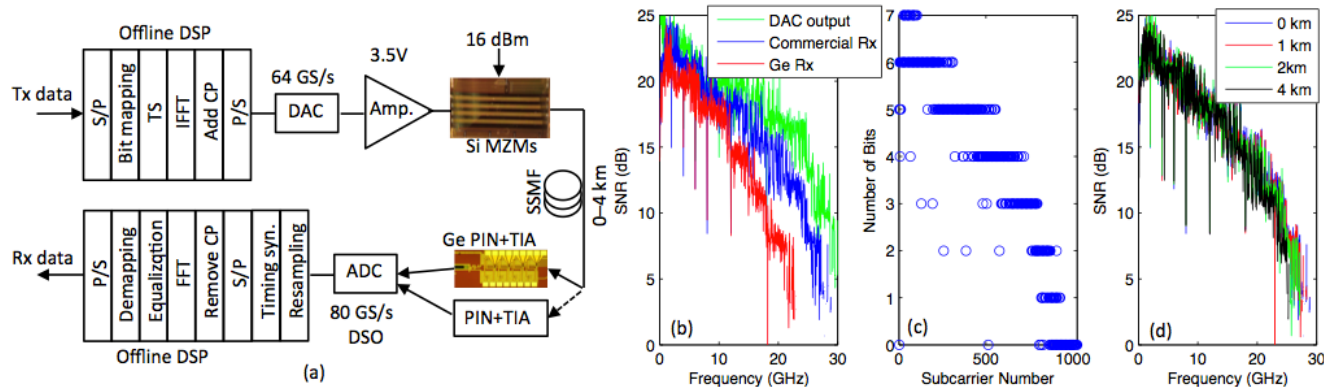


Fig. 2: (a) Experimental setup for DMT modulation, transmission and detection. (b) Measured SNRs per carrier. (c) Bit allocation per subcarrier after bit loading. (d) SNRs for different transmission lengths.

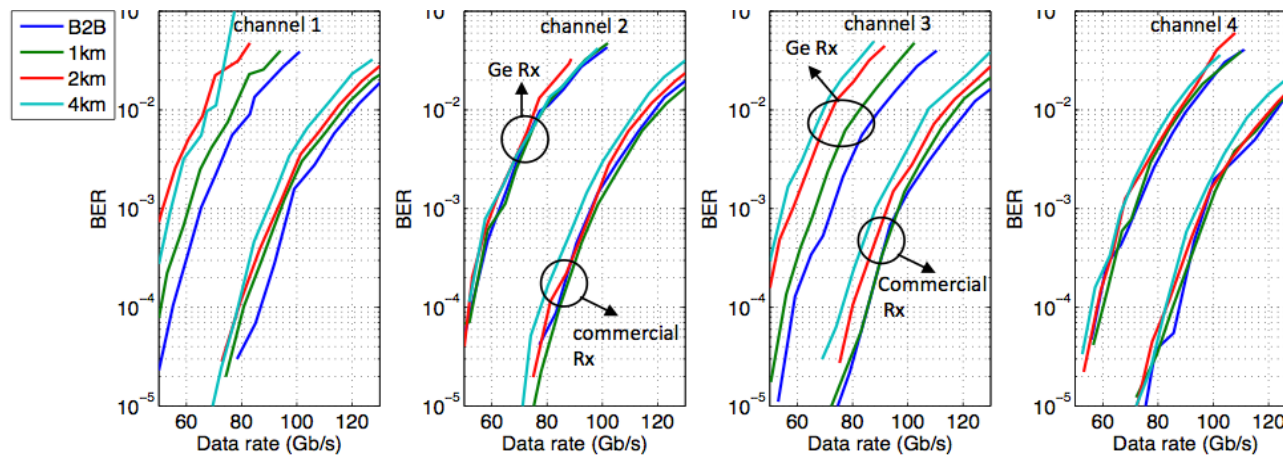
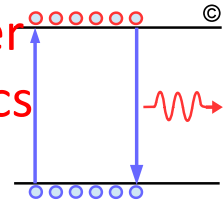


Fig. 3: BERs for four channels and different transmission distance. The group of higher data rates are for commercial receiver, while the others are for silicon-PIC receiver. When silicon-PIC receiver is used, channel  $i$  stands for the link from the MZM  $i$  to the Ge PD  $i$ .

# 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 50 Gb/s error floor of better 1E-8 demonstrated

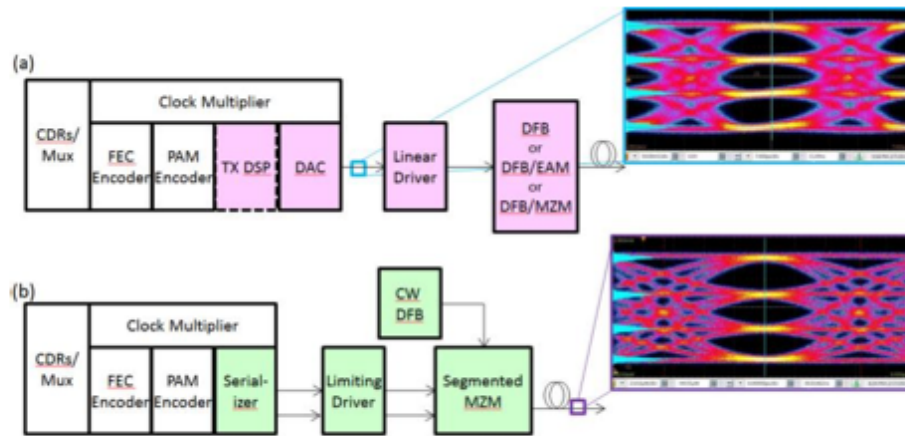


Fig.1: (a) DAC based PAM-4 transmitter block diagram with BCM82040 25GBaud PAM-4 electrical eye, and (b) Segmented MZI PAM-4 transmitter block diagram with Cisco PAM-4 optical eye diagrams.

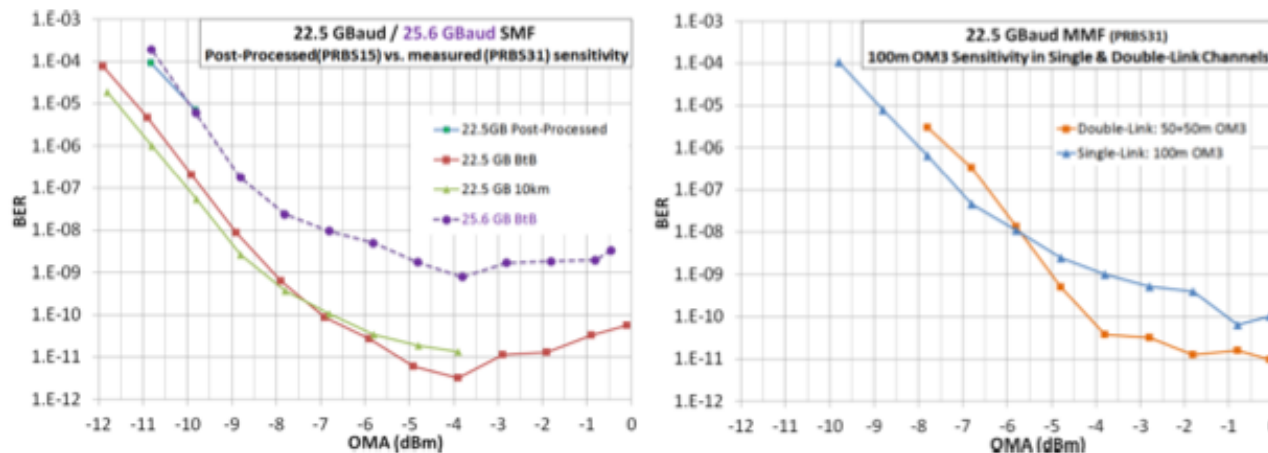
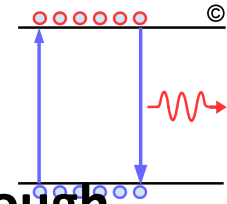


Fig.3: PAM-4 Sensitivity: (a) BtB and 10km SMF at 22.5GBaud and BtB at 25.6GBaud; (b) Single and double-link MMF at 22.5 GBaud.

# 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.