Nano Scale Disruptive Silicon-Plasmonic Platform for Chip-to-ChipInterconnection

Concept for System Integration developed

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List of Partners concerned

Partner number	Partner name	Partner short name	Country	Date enter project	Date exit project
1	Karlsruher Institut für Technologie	KIT	Germany	M1	M36
2	INTERUNIVERSITAIR MICRO-ELECTRONICA CENTRUM VZW	IMCV	Belgium	M1	M36
3	TECHNISCHE UNIVERSITEIT EINDHOVEN	TU/e	Netherlands	M1	M36
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Executive Summary

This document presents the main overview for the system integration that will be developed and demonstrated at the end of the project. System modeling has been updated according to the latest data available from NAVOLCHI partners studying each component of the targeted system. Identification of design tolerances for the modules under development has been achieved.Three scenarios have been identified for the integration, demonstration and performance evaluation of the NAVOLCHI system: In the first scenario the transmitter is based on the direct modulation of metallo-dielectric laser while in the second and third scenario the transmitter is based on the external laser with a plasmonic based, phase/amplitude MZ modulator respectively. In all cases the collector will be based on either a conventional Si/Ge photodetector, or a plasmonic Schottky one.

Change Records

Version	Date	Changes	Author
0.1 (draft)	2014-01-30	Start	Christoforos Kachris (AIT)
0.2	2014-02-10		Christoforos Kachris (AIT)
0.3	2014-03-26		Christoforos Kachris (AIT)
0.4	2014-10-15	Updated with the new values	ThymiosLallas (AIT)
0.5	2015-05-31	Updated with new data for DML scenario	ThymiosLallas (AIT)

Contents

1. Introduction

The NAVOLCHI system is a chip-to-chip interconnect that comprises of a plasmonic transmitter and a plasmonic receiver.Three scenarios have been identified for the integration, demonstration and performance evaluation of the NAVOLCHI system:

In the first scenario the transmitter is based on the direct modulation of metallo-dielectric laser, a directly modulated laser (DML) - based system in which the data are applied directly on the driving current of the metallo-dielectric laser source. In the second and third scenario the transmitter is based on the external laser with a phase/amplitude modulator respectively. Specifically, in the second scenario, system consists of a differential phase shift keying (DPSK) transmitter, utilizing the plasmonic MZM driven by the external laser source in continuous wave (CW) mode and with differential phase shift keying (DPSK) detection based on a passive delay line interferometer (DLI) at the receiver. In the third scenario system consists of an intensity modulation transmitter(OOK) utilizing the MZM and the laser source in CW mode, with direct detection at the receiver. In all cases the collector will be based on either a conventional Si/Ge photodetector, or a plasmonic Schottky one.

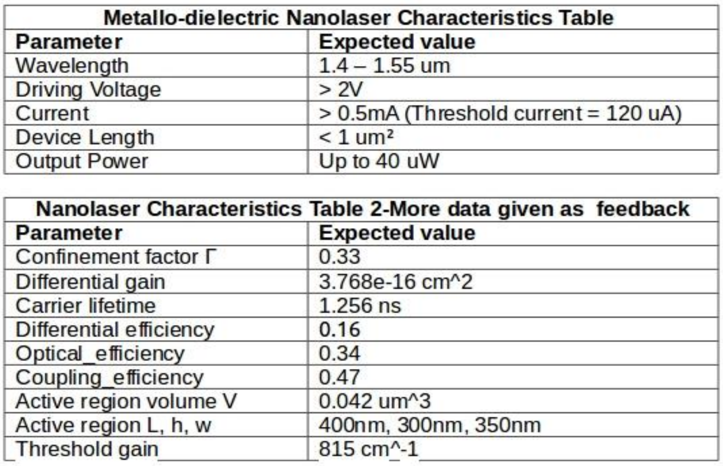
Note that while the system will consist of 4 similar parallel channels, we are only simulating one of the channels in the platform scenarios that follow(single mode).The simulation tool VPI Photonics is used as the basis for the platform.

A first approach on simulation and the performance evaluation of the considered scenarios had been presented in D2.3 “Investigation of chip-to-chip interconnection level specifications employing new plasmonic devices. In this document, system modeling has been updated according to the latest data available from NAVOLCHI partners studying each component of the targeted system.

2. Scenario-1:direct modulation of metallo-dielectric nanolaser(DML)

a)Scenario-1(DML)description:

In the directly modulated laser (DML) - based system, the data are applied directly on the driving current of the metallo-dielectric nanolaser source. Concerning DML laser we have used a VPI DFB laser model and we have set its parameters in such a way so that its output pulse profile to match exactly the sample data pulse profile we have received from our Navolchi partner, TU/e. Laser structure updated parameters, given as feedback by TU/e[2], are showed in Tables 1 and 2.



Metallo-dielectric Nanolaser Characteristics Table	
Parameter	**Expected value**
Wavelength	1.4 – 1.55 um
Driving Voltage	> 2V
Current	> 0.5mA (Threshold current = 120 uA)
Device Length	< 1 um^2
Output Power	Up to 40 uW

Nanolaser Characteristics Table 2-More data given as feedback	
Parameter	**Expected value**
Confinement factor Γ	0.33
Differential gain	3.768e-16 cm^2
Carrier lifetime	1.256 ns
Differential efficiency	0.16
Optical_efficiency	0.34
Coupling_efficiency	0.47
Active region volume V	0.042 um^3
Active region L, h, w	400nm, 300nm, 350nm
Threshold gain	815 cm^-1

Table 1 and 2:Nanolaser characteristics

External driving electronics would electrically pump the nanolaser, which will be coupled to a conventional fiber interconnection, before sending the signal to the receiver chip(Fig.1). An attenuator is placed between transmitter and receiver in order to simulate overall end to end system losses, mainly those come from conventional fiber interconnection. The photodetector could be either a conventional Si/Ge Photonics detector (IMEC feedback data)[1] or a Plasmonics detector (UVEG feedback data).Finally, at the end of the system a BER tester is used for measuring the system's BER performance.

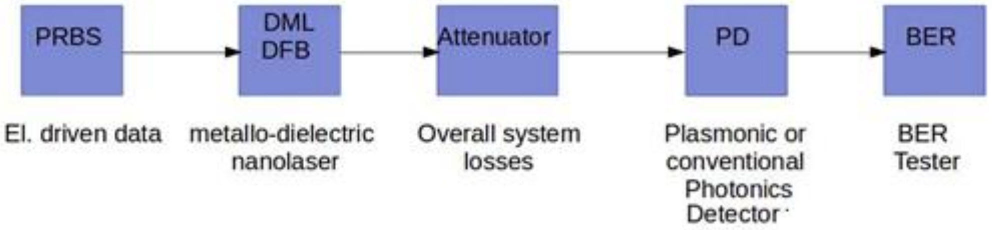


Figure 1:DMLscenario-1

b) Scenario-1 (DML)results

BER performance is estimated for various received powers in dBm, at proposed system bitrate (7.2Gbps), at lower and at higher system bitrates(1Gbps and 10Gbps), as shown in Figure 2:

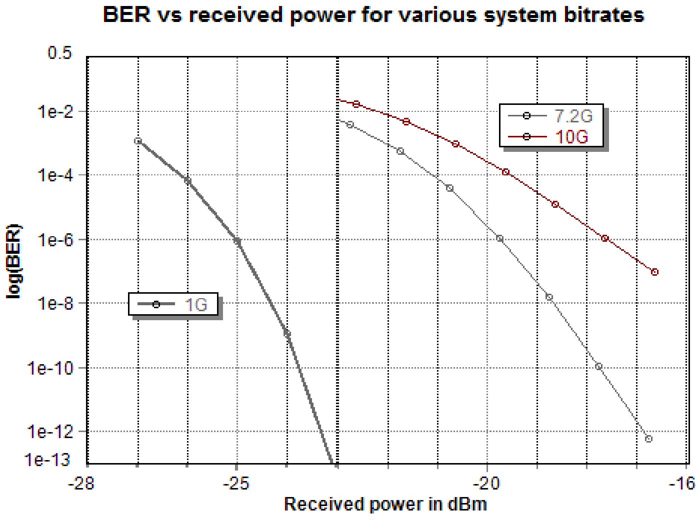


Figure 2:BER vs received power at various system bitrates

As seen in Figure 2, BER performance at 1Gbps system bit rate is much better than BER performances at higher bit rates (7.2Gbps and 10Gbps). In fact at higher bitrates, the same BER performance is achieved with that, at 1Gbps, but at higher received powers. For these measurements we have considered RIN effect at the laser source(-130dB/Hz), and a typical responsivity of 0.8A/W at the receiver. In Figure 3a we can see eye diagram of the signal at the output of the laser source, at 1Gbps, and in Figure 3b, the eye diagram of the signal after the PIN diode and its accompanying LPF, at 7.2Gbs, as a metric of the quality of the signal.

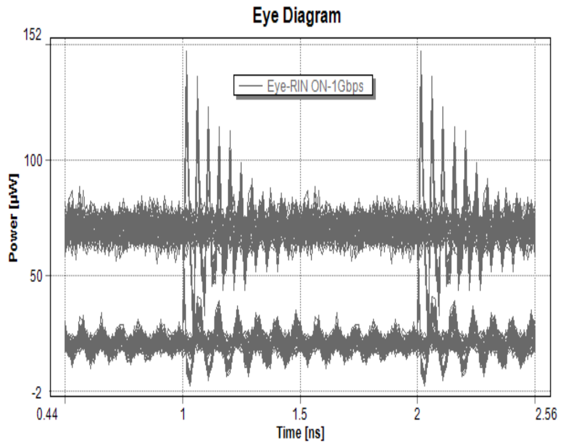


Figure 3a:Eye diagram at 1Gbps

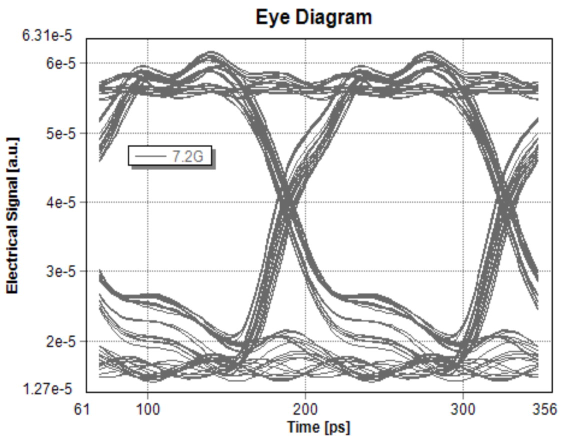
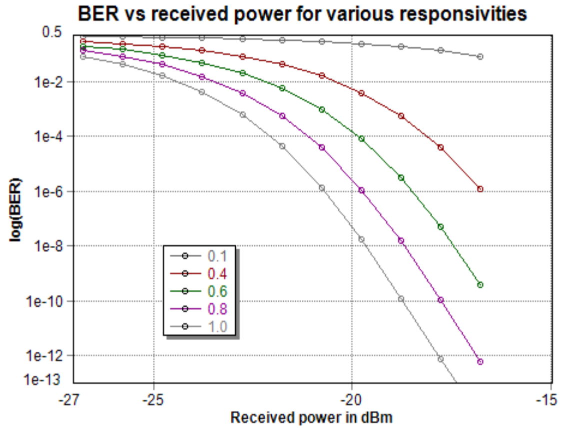


Figure 3b:Eye diagram at 7.2Gbps

BER performance is also estimated for various received powers in dBm, at proposed system bitrate (7.2Gbps), considering laser's RIN, for a range of receiver responsivities covering both cases, an IMEC conventional Si/Ge photoreceiver(0.4-0.6A/W), and a UVEG plasmonic photoreceiver(0.08-0.16A/W), as shown in Figure 4:



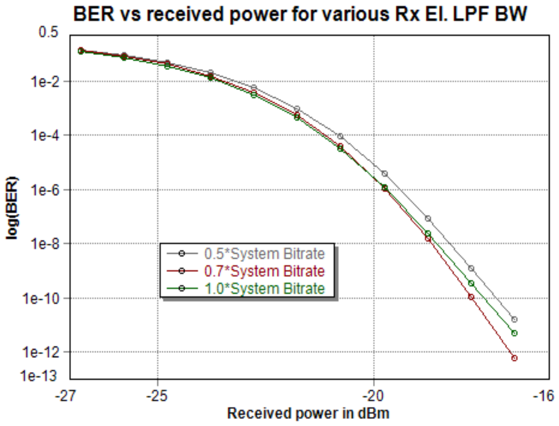


Figure 4:BER vs rec. power at various responsivities **Figure 5: BER vs rec. power at various Rx LPF BWs**

It seems that Plasmonic detector's responsivity is not enough to achieve satisfactory BER results. Conventional detector's responsivity (and even higher than 0.4A/W) is required for achieving acceptable BER. in Figure 5, BER performance is also estimated for various received powers in dBm, at proposed system bitrate (7.2Gbps), considering laser's RIN, for a range of receiver LPF bandwidths, at a typical responsivity of 0.8 A/W.

3. Scenarios 2 and 3: external laser with a phase/amplitude modulator(EML)

a) Scenarios 2 and 3(EML)description:

In the externally modulated laser (EML) - based system the transmitter is based on the external laser with a phase/amplitude modulator respectively. Specifically, in the second scenario, system consists of a differential phase shift keying (DPSK) transmitter, utilizing the plasmonic MZM driven by the external laser source in continuous wave (CW) mode and with differential phase shift keying (DPSK) detection based on a passive delay line interferometer (DLI) at the receiver(Figure 6).

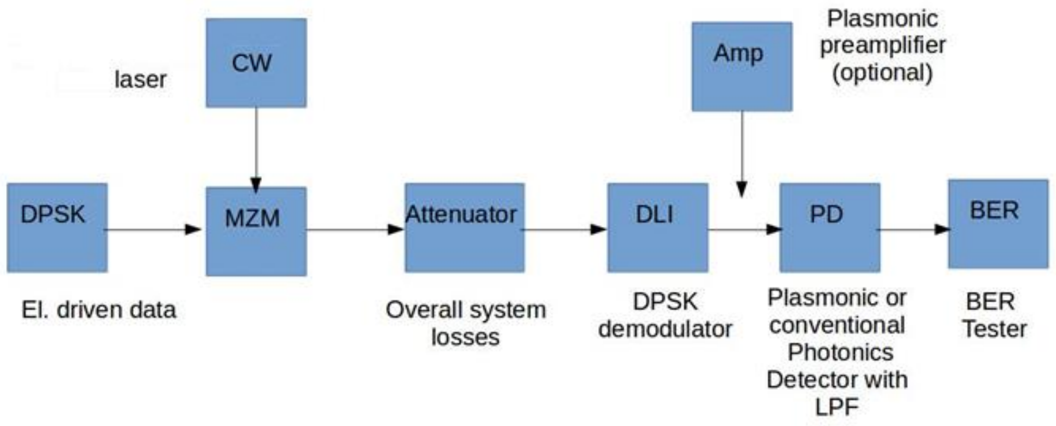


Figure 6:EML DPSK scenario

In the third scenario, system consists of an intensity modulation transmitter(OOK) utilizing the MZM and the laser source in CW mode, with direct detection at the receiver(Figure 7).

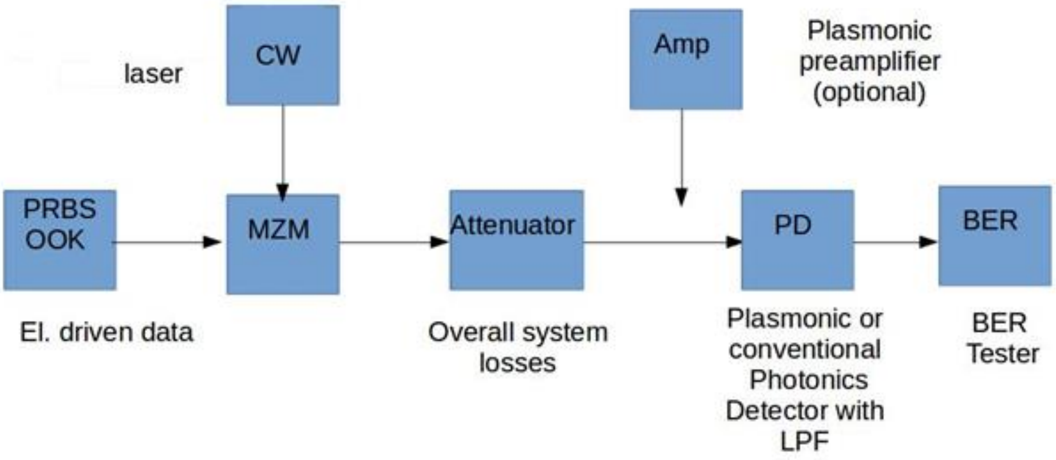
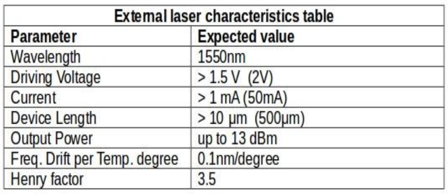
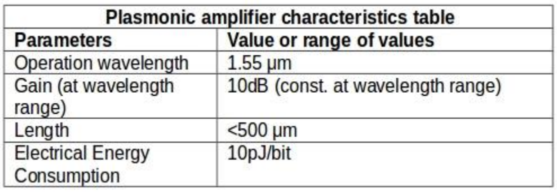


Figure 7: EML OOK scenario

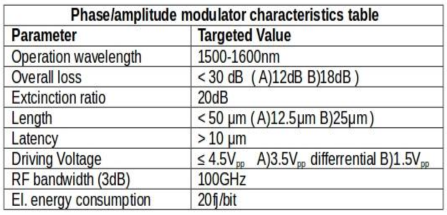
In both scenarios, the collector will be based on either a conventional Si/Ge photodetector, or a plasmonic Schottky one, and at the end of the system, there will be a BER tester in order to measure system BER performance, as in DML first scenario. An attenuator is placed between transmitter and receiver in order to simulate overall end to end system losses, which include: a)mainly losses come from chip to chip conventional fiber interconnection, b) fiber losses between CW external laser and MZM chip and c) coupling losses between plasmonic amplifier and detector(in cases a preamplifier is used). Plasmonic based MZM modulator has its overall loses as well. They can be attributed to: a) propagation losses across the Plasmonic Phase Shifter length(PPS) and b) coupling losses due to photonic Multi Mode Interference coupler(MMI) and due to photonic to plasmonic taper coupler[2],[4]. An adequate number of targeted parameters have been provided for the MZM (also being evaluated experimentally), thus allowing for an accurate evaluation of both scenarios system performance. Characteristic parameter tables for all devices participate at EML scenarios 2 and 3 are seen below. Concerning photodetector characteristics table, the same one, applies to DML scenario as well:



External laser characteristics table	
Parameter	**Expected value**
Wavelength	1550nm
Driving Voltage	> 1.5 V (2V)
Current	> 1 mA (50mA)
Device Length	> 10 μm (500μm)
Output Power	up to 13 dBm
Freq. Drift per Temp. degree	0.1nm/degree
Henry factor	3.5



Plasmonic amplifier characteristics table	
Parameters	**Value or range of values**
Operation wavelength	1.55 μm
Gain (at wavelength range)	10dB (const. at wavelength range)
Length	<500 μm
Electrical Energy Consumption	10pJ/bit



Phase/amplitude modulator characteristics table	
Parameter	**Targeted Value**
Operation wavelength	1500-1600nm
Overall loss	< 30 dB (A)12dB B)18dB)
Extcinction ratio	20dB
Length	< 50 μm (A)12.5μm B)25μm)
Latency	> 10 μm
Driving Voltage	≤ 4.5V_{pp} A)3.5V_{pp} differrential B)1.5V_{pp}
RF bandwidth (3dB)	100GHz
El. energy consumption	20fj/bit

Photodetector characteristics table		
	Conventional Si/Ge	**Plasmonic Schottky**
Parameter	**Targeted Value**	**Targeted Value**
Reponsivity	0.4 A/W 1550nm	0.08-0.16 1550nm
Dark Current	<100nA	70nA
BW	30-40GHz	tested

Tables 3- 6:System device characteristics tables

b) Scenarios 2 and 3(EML) results

For both scenarios 2 and 3, BER performance at specified bitrate (7.2Gbps) is estimated for maximum overall losses that the system can handle, for range of values of various critical parameters:a)MZM overall losses b)detector responsivities(for both conventional Si/Ge and plasmonic detectors), c)other system bitrates and d)Noise Figure value range in case an amplifier is used(Gain:10dB which is the NAVOLCHI target value).Measurements of BER performance versus chip to chip interconnection distance at specified bitrate and other bitrates can be easily extracted, as long as, data values of interconnection loss in dB/mm and typical ranges of chip to chip interconnection distances are required to be given as data.

b1) Scenarios 2 (EML DPSK) results

BER performance is estimated for maximum overall losses that the system can handle, at proposed system bitrate (7.2Gbps) for two critical MZM overall losses(18dB and 12dB), as shown in Figure 8(Laser output power is set at 10dBm, and the detector’s responsivity at 0.4A/W):

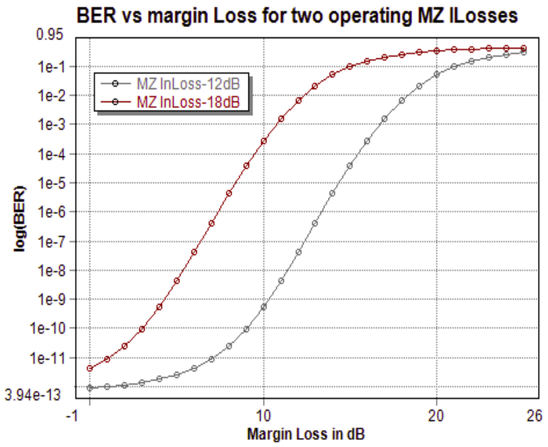


Figure 8

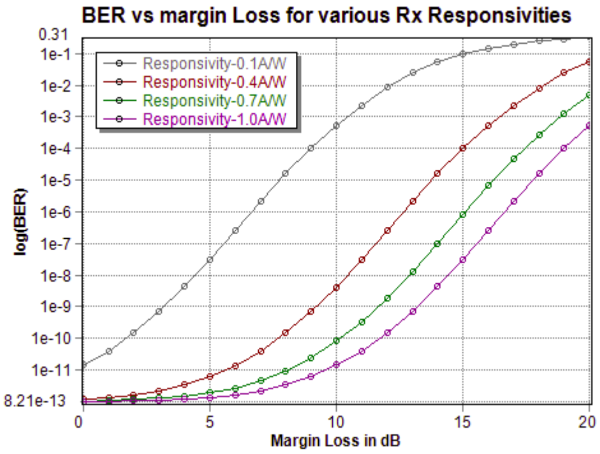


Figure 9

As can be seen, BER performances can be significantly improved by reducing MZM total losses(from 18 to 12dB), especially when system is to be operated at higher than default bit rate (7.2Gbps). Concerning detector's critical parameters effect on system behavior, BER performance is estimated for maximum overall losses that the system can handle, at proposed system bitrate (7.2Gbps) for a range of receiver responsivities covering both cases, an IMEC conventional Si/Ge photoreceiver(0.4-0.6A/W), and a UVEG plasmonic photoreceiver(0.08-0.16A/W), as shown in Figure 9(Laser output power is set at 10dBm, and MZM loss at 12dB). External laser scenario shows good BER performances even for the lowest responsivity for system losses up to 10dB.

Figure 10 shows system BER performance for a range of overall losses for higher than default system bitrates. System shows quite good BER performance for bit rates up to 20Gbps and overall losses up to 15dB.

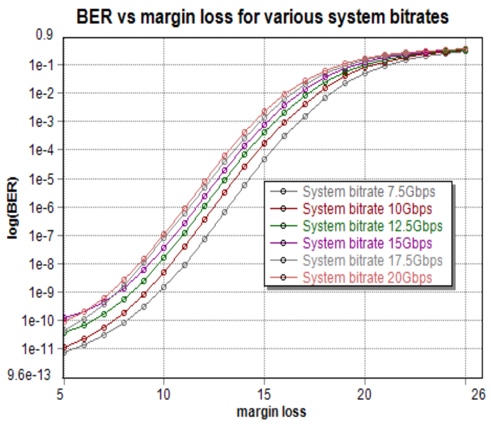


Figure 10

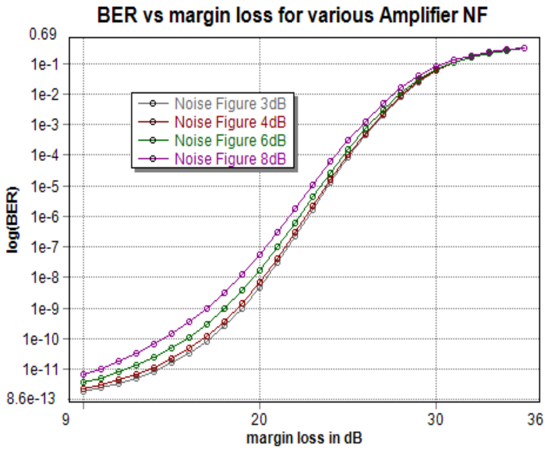


Figure 11

Finally, Figure 11 shows BER performance for a range of overall losses at default bit rate when placing an amplifier prior to detector, at constant Gain of 10dB, which is Navolchi’s target value, for various Noise Figures. System shows good BER performance for quite all NF range for total system loss around 20dB.

b2) Scenarios 3 (EML OOK) results

BER performance is estimated for maximum overall losses that the system can handle, at proposed system bitrate (7.2Gbps) for two critical MZM overall losses(18dB and 12dB), as shown in Figure 12(Laser output power is set at 10dBm, and the detector’s responsivity at 0.4A/W):

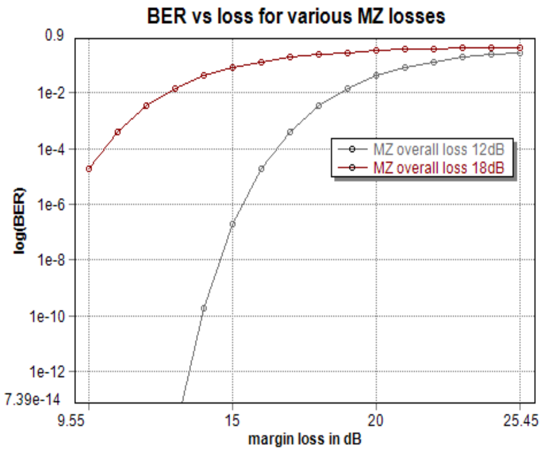


Figure 12

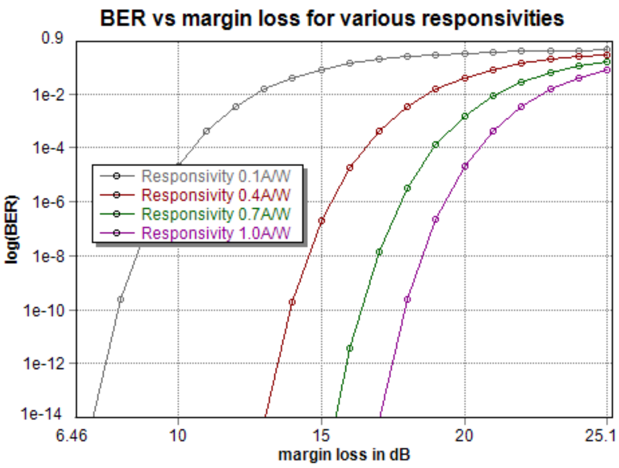


Figure 13

As can be seen, BER performances can be significantly improved by reducing MZM total losses, and the improvements will be greater than DPSK scenario. In Figure 13, BER performance is estimated for maximum overall losses that the system can handle, at proposed system bitrate (7.2Gbps) for a range of receiver responsivities covering both photoreceiver cases (Laser output power is set at 10dBm, and MZM loss at 12dB). Again, OOK scenario shows adequate BER performance even for the lowest responsivity for system losses up to 10dB.

Figure 14 shows system BER performance for a range of overall losses for higher than default system bitrates. System shows quite good BER performance for all range of bit rates and for overall losses up to 15dB.

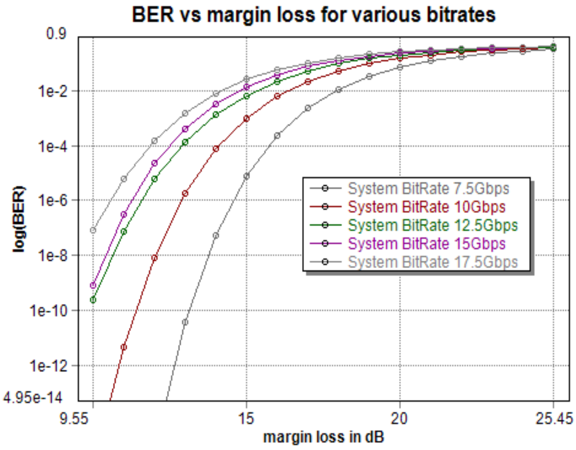


Figure 14

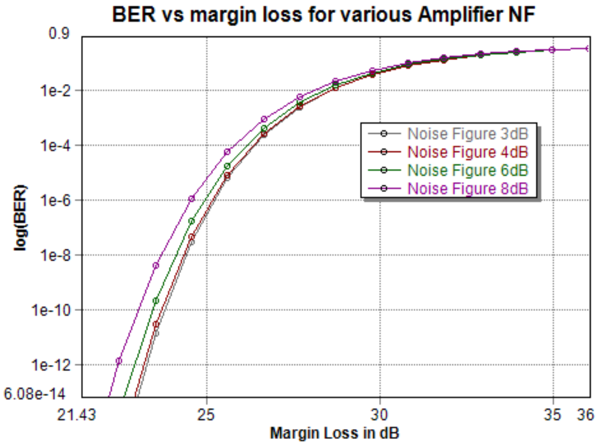


Figure 15

Finally, Figure 15 shows BER performance for a range of overall losses at default bit rate when placing an amplifier prior to detector, at constant Gain of 10dB, which is Navolchi's target value, for various Noise Figures. System shows good BER performance for quite all NF range for total system loss up to 25dB.

4. Conclusions

A simulation platform has been developed with the commercial VPI Photonics software and the NAVOLCHI chip to chip interconnect system has been studied. Three different scenarios have been studied in total: direct laser modulation(DML) and external modulated scenarios, with external phase or amplitude modulation(EML DPSK, and EML OOK respectively).

The Bit Error Rate has been calculated for each case, as a system performance means of measurements by sweeping parameters such as the received power or the laser output power or the MZM losses, or amplifier Noise Figure, or receiver sensitivity for default system bitrate(7.2Gbps), and at higher or lower bitrates. Other parameters such as MZ extinction ratio, or laser's linewidth, or receiver's dark current, to name but a few, have been tried out as well, but they didn't seem to affect system BER behavior.

Direclty modulated (DML) scenario shows poor BER performance at Navolchi bitrate(7.2Gbps) for such low typical operating nanolaser powers(20-70uW), and at typical conventional receiver's operating responsivities, while at plasmonic typical responsivities, it doesn't seem to operate properly. However, the DML system shows good BER performance at lower bit rates(1Gbps).

On the contrary, both EML simulation scenarios have been extensively carried out, since MZM plasmonic device, has been fully characterized, and hence there is a much more accurate view on system behavior. Obviously, external laser scenarios with MZM show better BER performances than DML but they can be significantly improved by reducing MZM total losses(up to 12dB), especially when system is to be operated at higher than default bit rate (7.2Gbps).Moreover, external laser scenario performance can be greatly enhanced by placing an optical amplifier prior to detector, extending system total loss margins.

5. References

[1] Peter Verheyen, Guy Lepage, Joris Van Campenhout, Marianna Pantouvaki, Philippe Absil, P. De Heyn, W. Bogaerts, P. Dumon, S. Selvaraja, Co-integration of Ge detectors and Si modulators in an advanced Si photonics platform, SPIE Photonics Europe 2012, 8431, Belgium, p.paper 39 (2012)

[2] Dolores Calzadilla, V.M., Heiss, D., Fiore, A. & Smit, M.K. "Metallo-dielectric nanolaser coupled to an InP-membrane waveguide" Proceedings of the 17th Annual Symposium of the IEEE Photonics Society Benelux Chapter, 29-30 November 2012, Mons, Belgium, Mons

[3] Melikyan et al., "High-speed plasmonic phase modulators" Nat Photon, vol.8, no.3, pp.229-233,(2014)

[4] J. Leuthold et al., "High-speed plasmonic Mach-Zehnder modulator in a waveguide" PD.2.6, 25/9/2014, Cannes, ECOC 2014