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

Investigation of chip-to-chip interconnection level specifications employing new plasmonic devices

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Executive Summary

The present document reports on the simulation results for the NAVOLCHI concept. Specifically, it presents the results of the simulated model that integrated the chip-to-chip interconnection scheme employing the plasmonic devices. The simulation platform has been realized with the commercial VPI Photonics software. Eight different configurations have been studied in total: with direct or indirect modulation, with plasmonic or PIN detector, with or without amplifier. The Bit Error Rate has been calculated for each case, sweeping parameters such as the laser output power or the amplifier gain. The study is focused on the question of device characteristics, so that the system target specifications are achieved. The eight different configurations that have been studied is part of the design space exploration that has been performed in order to find the configuration that better meets the system requirements. However, the exact configuration that will be implemented and demonstrated at the end of the project will depend on the final characteristics of the implemented components and the simulation models will be updated to better reflect the component's features.

Change Records

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Contents

1. Introduction

This document presents the NAVOLCHI system simulation platform and reports the first results based on the input of device leaders. The NAVOLCHI system is a chip-to-chip interconnect that comprises a plasmonic transmitter and a plasmonic receiver. The plasmonic transmitter consists of a metallo-dielectric laser and a plasmonic modulator. The plasmonic receiver consists of a plasmonic pre-amplifier and a plasmonic photodetector. Gratings are used to couple light out of and into the chips. See D2.2 and the Intermediate Report, WP2 section, for more details on the system and its components.

Note that while the system will consist of 4 similar (ideally: same) parallel channels, we are only simulating one of the channels in the platform scenarios that follow.

The simulation platform presented here is used for the evaluation of the device specs in relation to the system specs. The aim of this process is to provide feedback and guide the device leaders so that the system specs are ultimately achieved.

The simulation tool VPI Photonics is used as the basis for the platform. Examples of the platform for different system scenarios that are being considered are given in the figures below, where the subsystems are visible. Within VPI, there are two different ways to program each subsystem module. The first possibility is to use VPI's available internal generic modules to simulate each subsystem. In this case, the VPI user can enter the subsystem properties (as given by the device leaders) into the available input interfaces of VPI. A second possiblity is to bypass VPI's generic modules and replace them with Matlab files (that cooperate with VPI) in order to simulate the finer details of each subsystem. The plan is to start with the first possiblity (using the VPI's available generic modules) and eventually only replace the modules that prove to need additional details from a system perspective. Such replacements are going to be decided in view of the device testing results that are under progress.

At the time that this report is written, the NAVOLCHI devices (that will comprise the system) are not fabricated yet or are not in an acceptable state for the NAVOLCHI demonstrator. For this reason, a lot of the parameters used are estimates or targets, as will be noted in detail in the relevant section.

2. Systems under investigation

The potential system configurations under investigation are shown in the following figures.

In Figure 1 you can see the indirect modulation scenario. The metallic nanolaser feeds the plasmonic modulator. The modulator sends the modulated signal to the receiver chip, where it goes through the plasmonic amplifier before ending up in the photodetector. The laser, the modulator and the receiver are on 3 different chips. The communication between the chips is established by gratings to send and receive the signal.

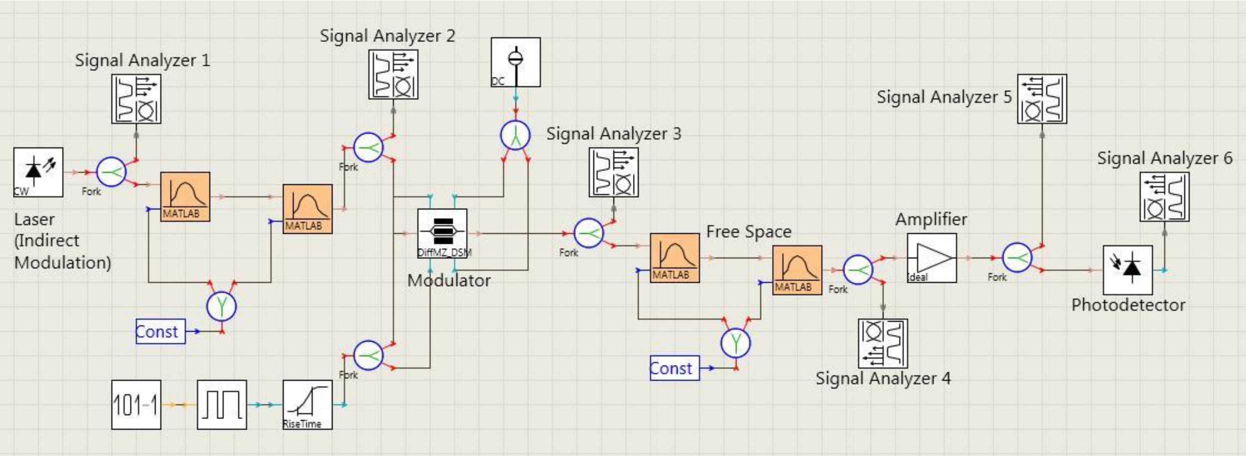


Figure 1 Indirect modulation scenario with plasmonic amplifier.

The indirect modulation scenario will be studied with two different photodetectors. A plasmonic one from UVEG and a standard PIN one from IMEC. In addition, each case will be studied with and without the amplifier. See the indirect modulation scenario without the amplifier in Figure 2.

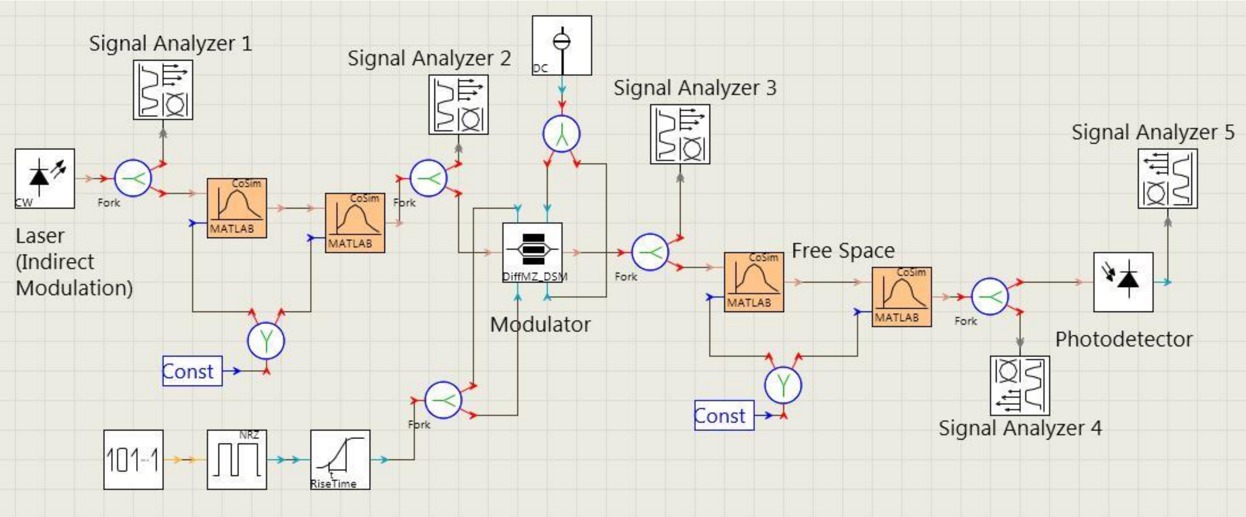


Figure 2 Indirect modulation scenario without a plasmonic amplifier at the receiver.

Then, we also study the same system with direct modulation. The idea here is that the power of the metallo-dielectric laser is low (~ 50 μW) and maybe that will not be enough to cooperate with the plasmonic modulator. We will elaborate on the issue in the Results section. The direct modulation scenario is shown in Figs. 3 & 4.

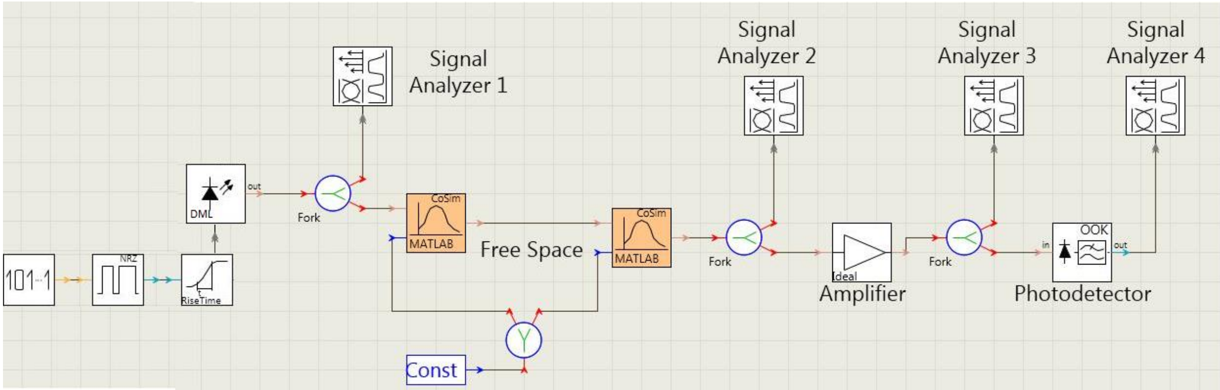


Figure 3 Direct modulation scenario with plasmonic amplifier.

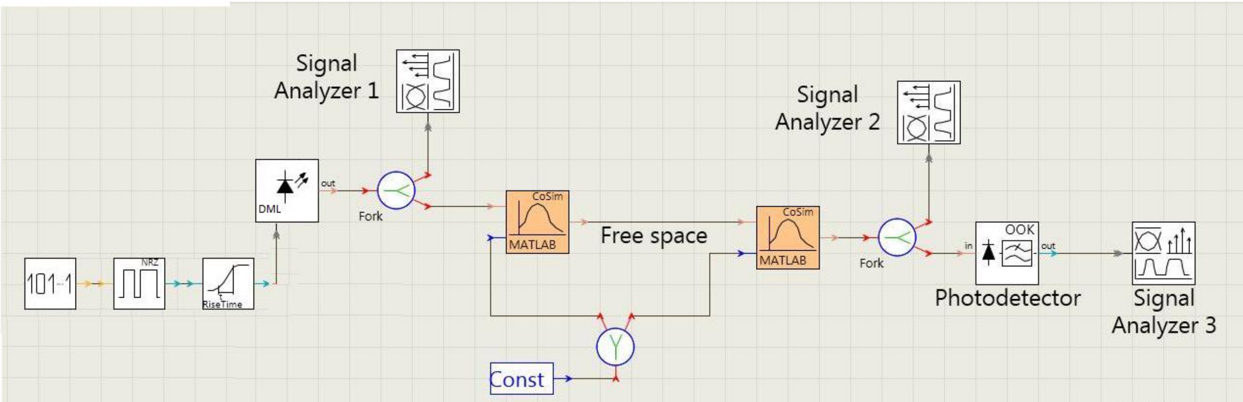


Figure 4 Direct modulation scenario without plasmonic amplifier.

All scenarios have been simulated with the receiver comprising (a) PIN detector from IMEC, or (b) plasmonic detector developed at UVEG.

For all approaches, each device can be modeled either by changing the parameters that VPI provides or through Matlab (through the Cosimulation VPI package). Cosimulation enables us to implement new simulation modules, additional to those provided by VPIphotonics. At the time when this deliverable is submitted, the gatings are simulated in Matlab. The platform is moddable, so that in the future any device can be replaced with a Matlab-algorithm.

3. Statement of Purpose

The latest system goals have been reported in the Intermediate Report. The data rate is set to 7.2 Gb/s (per channel). The simulation platform is going to calculate the eye diagrams and bit error rates (BERs) at different points in the system. The results will provide information on the transmission quality of the system and also show what devices cause major problems if quality is not acceptable.

4. Results

Indirect modulation

The main device parameters used for the indirect modulation simulations are the following:

Metallo-dielectric Laser: DC emission at 1550 nm, power at 50 μW (but other powers have been simulated too).
Plasmonic Modulator: phase modulator in mach-zehnder configuration, biased at optimal conditions, insertion loss at 10 dB. Extinction ratio simulated below. Bit rate 7.2 Gb/s.
Gratings: advanced gratings from IMEC with 2dB loss.
Plasmonic amplifier: Maximum output power at 0.2 W, Noise Figure 4 dB, Noise Bandwidth 25 THz. The gain goal within NAVOLCHI is 10 dB, but various gains have been simulated.
PIN Detector: Responsivity 0.5 A/W, dark current 100 nA, thermal noise 10 pA/Hz^(1/2).
Plasmonic Detector: Responsivity 0.1 A/W, dark current 1 μA, thermal noise 25 fA/Hz^(1/2).

Note that at this stage most of the above values are expected or estimated.

First, let's take a look at the scenario where the plasmonic detector is used without a plasmonic amplifier. At a laser output power of 50 μW and an extinction ratio of 12 dB, the BER is calculated to be an unacceptable 0.27 dB. Figure 5 shows the how BER is related to the laser output power.

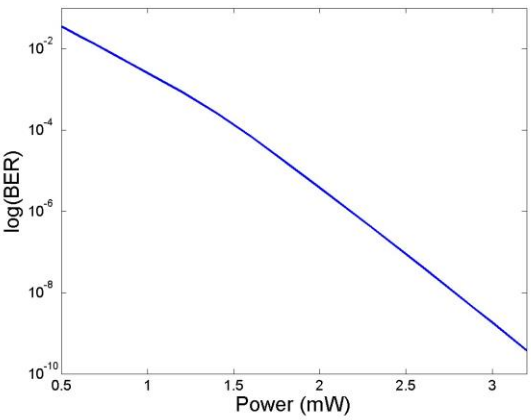


Figure 5 Scenario with indirect modulation and plasmonic photodetector, without plasmonic amplifier. BER vs laser output power. Extinction ratio is set at 12 dB.

We see that BER is 2.5e-3 dB at 1 mW, 3.8e-6 dB at 2 mW, and only falls < 1e-9 dB at powers greater than 3 mW. The expected output power of the metallo-dielectric laser is 50 μW, and therefore too low for this system.

We next set the laser power at 3 mW and calculate BER vs the modulator extinction ratio. The result is shown in Fig. 6.

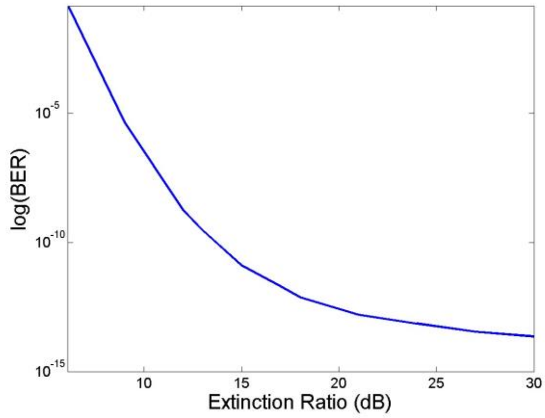
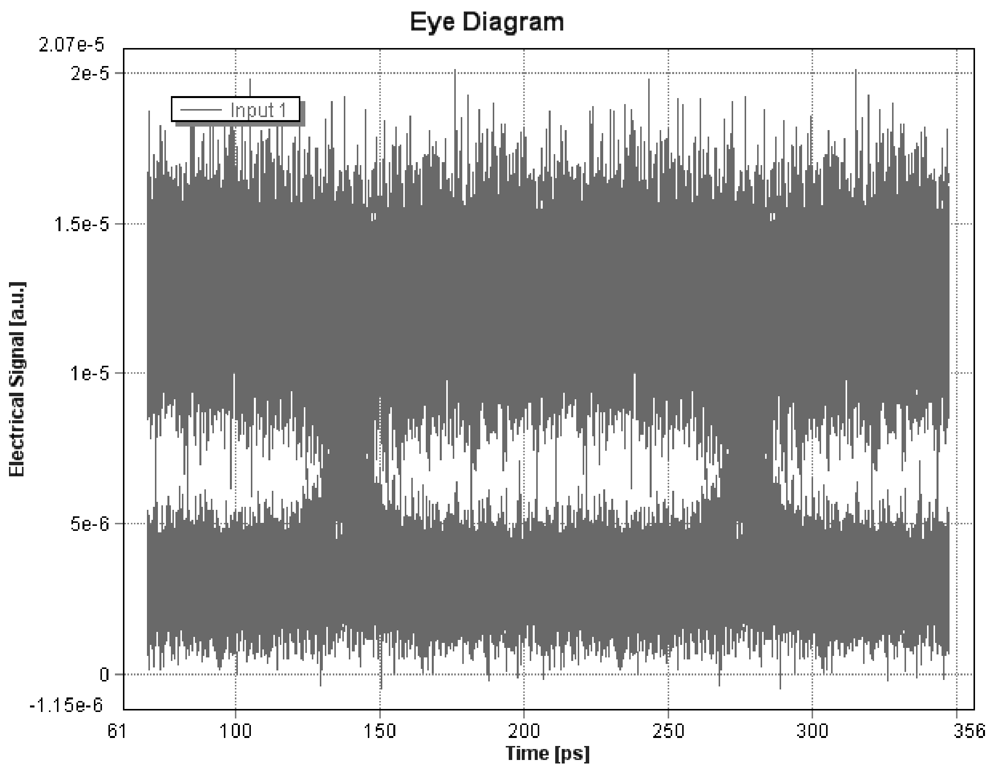


Figure 6 Indirect modulation scenario with plasmonic detector, without plasmonic amplifier. BER vs Extinction Ratio of modulator. Laser power is set at 3 mW.

We note that BER is 4.5e-6 dB at an extinction ratio of 9 dB, 1.8 dB at an extinction ratio of 12 dB, and 1.3e-11 dB at an extinction ratio of 15 dB. Fig. 7 shows the eye diagrams for the cases with an extinction ratio of 9 and 12 dB.



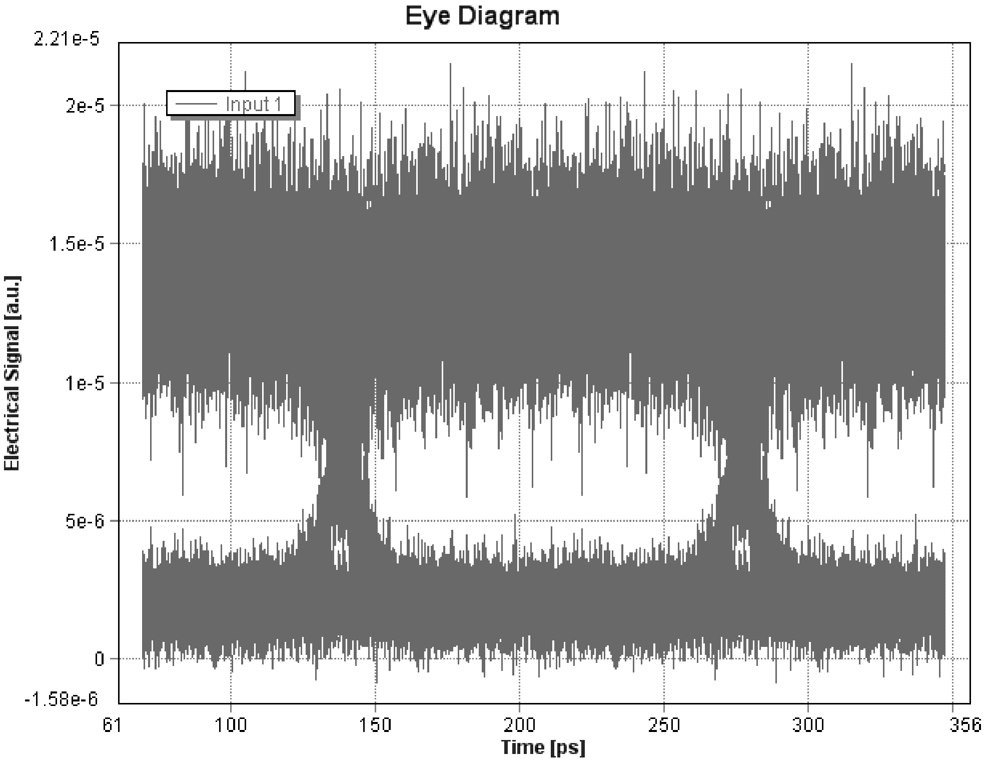


Figure 7 Indirect modulation scenario, with plasmonic detector and without plasmonic amplifier for the same received power. Eye diagrams at a laser power of 3 mW, for an extinction ratio of 9 (upper) and 12 (bottom) dB.

Next, we consider the same system with the addition of a plasmonic amplifier at the receiver chip. The amplifier increases the signal power, but also adds noise. At a laser power of 50 μW and an amplifier gain of 10 dB, the BER turns out to be an unacceptable 0.11 dB. The BER vs laser power diagram is shown in Fig. 8.

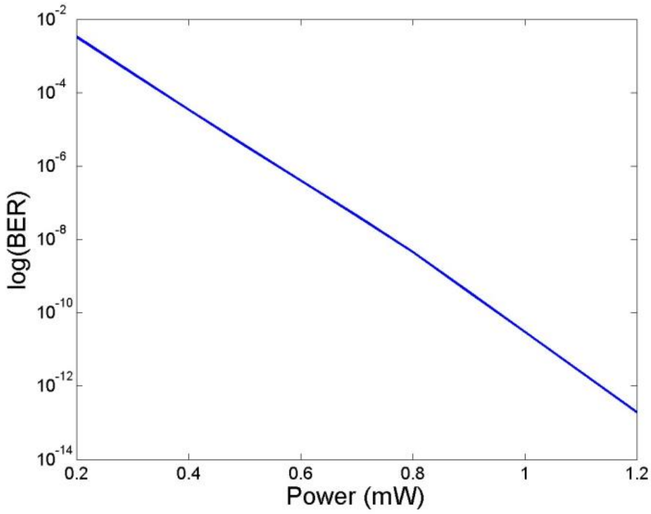


Figure 8 Indirect modulation with plasmonic detector and amplifier. BER vs Power. The modulator extinction ratio is 12 dB and the amplifier gain is 10 dB.

BER is 3.64e-6 dB at 0.5 mW, 4.36e-8 dB at 0.7 mW, and 3.67e-10 dB at 0.9 mW. Therefore, with an amplifier gain of 10 dB, still several hundreds of μWs are needed at the laser output.

We next set the laser power at 0.8 mW and calculate BER vs amplifier gain at an extinction ratio of 12 dB. The result is shown in Fig. 9.

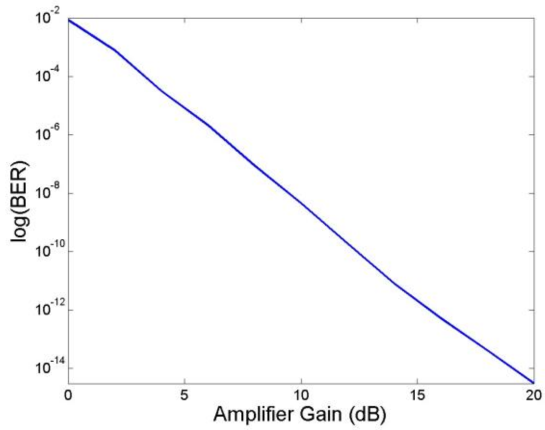


Figure 9 Indirect modulation with plasmonic detector and amplifier. BER vs Amplifier Gain. Laser power is 0.8 mW and modulator extinction ratio is 12 dB.

We see that BER < 1e-8 for amplifier gains greater than 9 dB (for ext. ratio 12 dB and laser output power of 0.8 mW).
Next, we study the influence of the modulator extinction ratio on BER. The results are shown on Fig. 10 for a laser power of 0.8 mW and an amplifier gain of 10 dB.

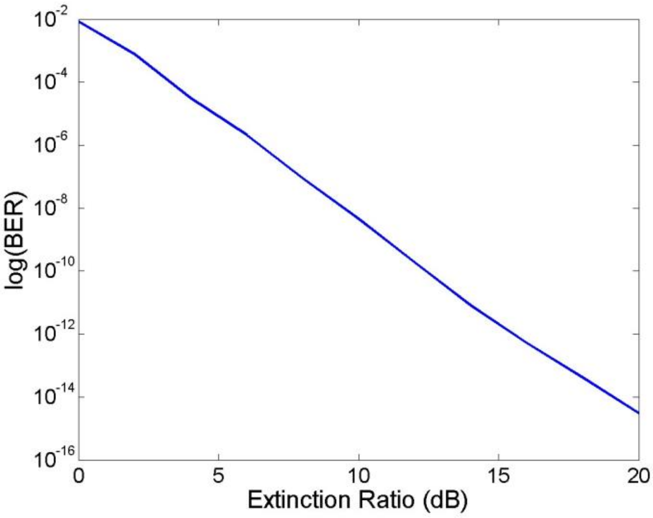
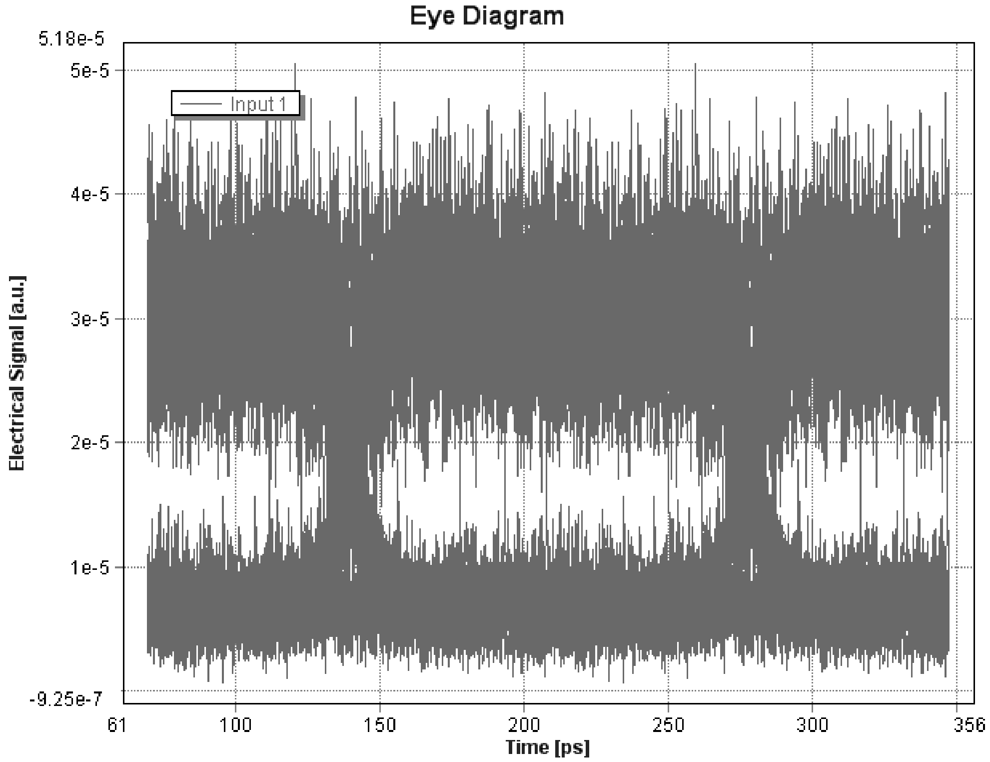


Figure 10 Indirect modulation with plasmonic detector and amplifier. BER vs Extinction Ratio of modulator. Laser power is 0.8 mW and amplifier gain is 10 dB.

We note that BER < 4.5e-9 dB for extinction ratios greater than 12 dB. Fig. 11 shows the eye diagrams for the cases with an extinction ratio of 9 and 12 dB. The respective BERs are 6.8e-6 and 4.5e-9 dB.



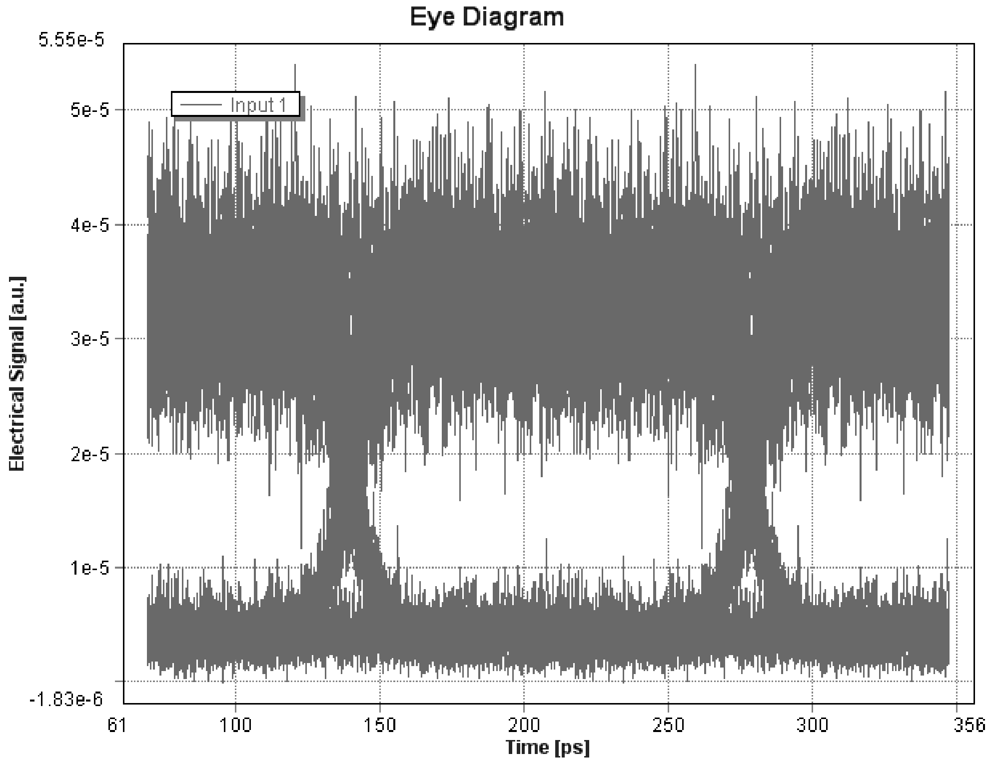


Figure 11 Indirect modulation scenario, with plasmonic detector and with plasmonic amplifier for the same received power. Eye diagrams at a laser power of 0.8 mW, for an extinction ratio of 9 (upper) and 12 (bottom) dB.

We did the same calculations for the case when the PIN detector is used instead of the plasmonic one. The PIN detector has greater responsivity (0.5 vs 0.1 A/W), smaller dark current (0.1 vs 1 μW), but worse thermal noise (10 vs 0.025 pA/Hz^(1/2)) than the plasmonic detector. However, please note that the plasmonic photodetector properties are merely estimated at this point.

As in the previous case, let's take a look at the scenario where the PIN detector is used without a plasmonic amplifier. At a laser output power of 50 μW and an extinction ratio of 12 dB, the BER is calculated to be an unacceptable 0.29 dB. Table 1 shows the how BER is related to the laser output power.

Table 1 Scenario with indirect modulation and PIN photodetector, without plasmonic amplifier. BER vs laser output power. Extinction ratio is set at 12 dB.

Laser power (mW)	BER (dB)
0.05	0.29
0.5	$4x10^{-4}$
0.6	$3.5x10^{-5}$
0.7	$2.1x10^{-6}$
0.8	$9.4x10^{-8}$
0.9	$3x10^{-9}$
1	$7.5x10^{-11}$

We next set the laser power at 0.9 mW and calculate BER vs the modulator extinction ratio. The result is shown in Fig. 12.

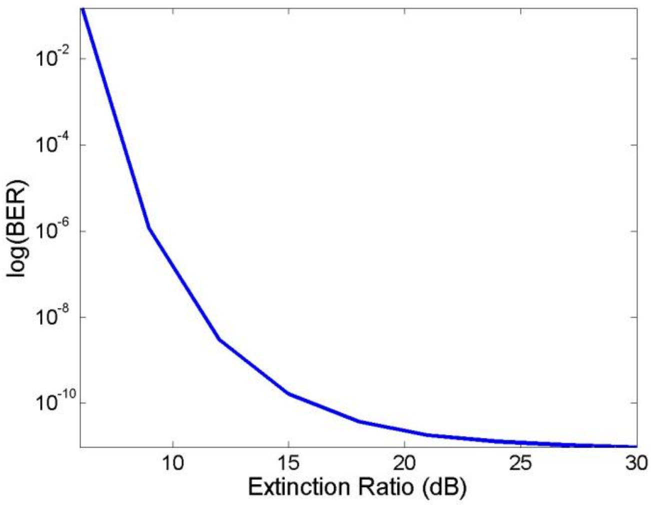
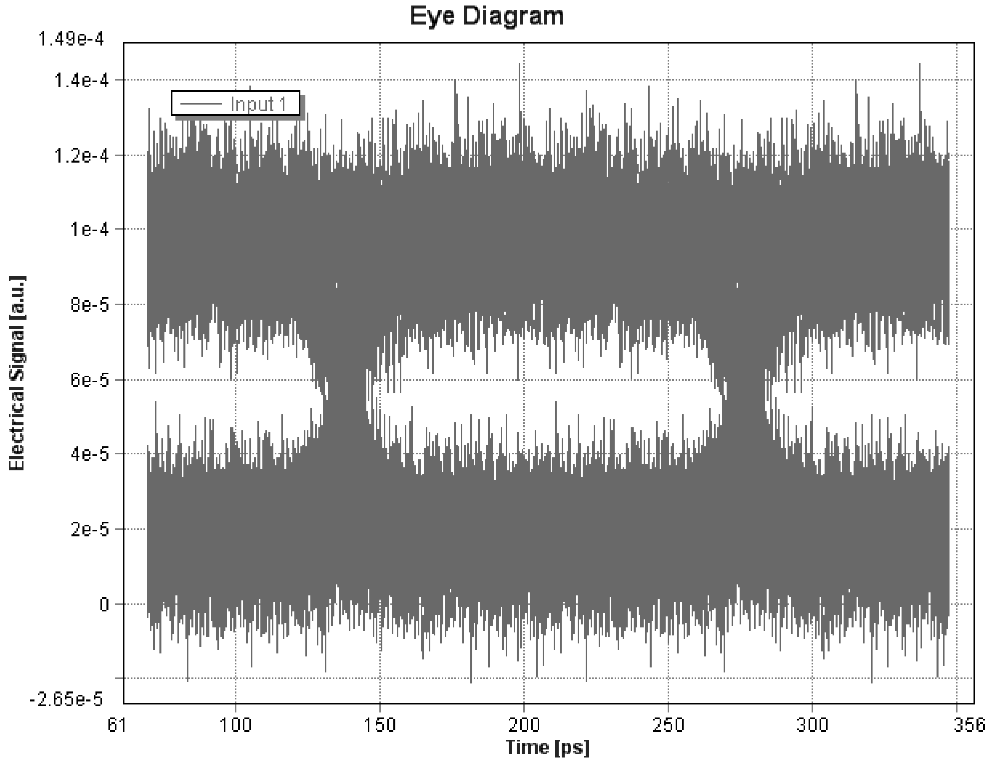


Figure 12 Indirect modulation scenario with PIN detector, without plasmonic amplifier. BER vs Extinction Ratio of modulator. Laser power is set at 0.9 mW.

We note that BER is 1.1e-6 dB at an extinction ratio of 9 dB, 3e-9 dB at an extinction ratio of 12 dB, and 1.65e-10 dB at an extinction ratio of 15 dB. Fig. 13 shows the eye diagrams for the cases with an extinction ratio of 9 and 12 dB.



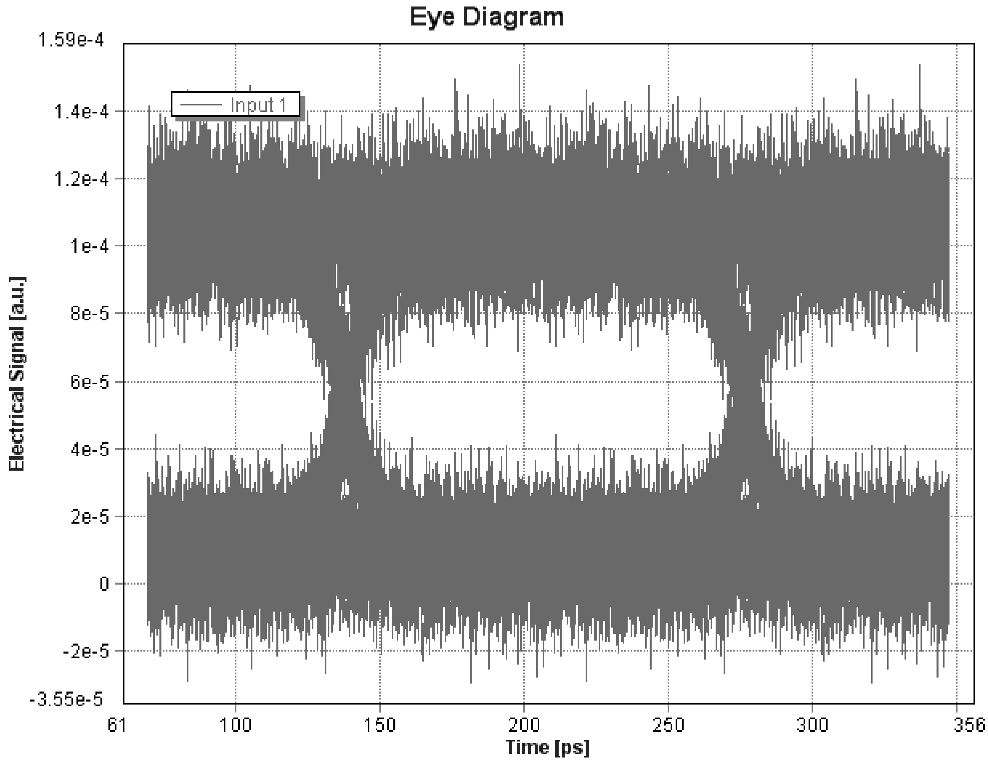


Figure 13 Indirect modulation scenario, with PIN detector and without plasmonic amplifier. Eye diagrams at a laser power of 0.9 mW, for an extinction ratio of 9 (upper) and 12 (bottom) dB.

Next, we consider the same system with the addition of a plasmonic amplifier at the receiver chip. At a laser power of 50 μW and an amplifier gain of 10 dB, the BER turns out to be an unacceptable 0.22 dB. The BER vs laser power diagram is shown in Figure 14.

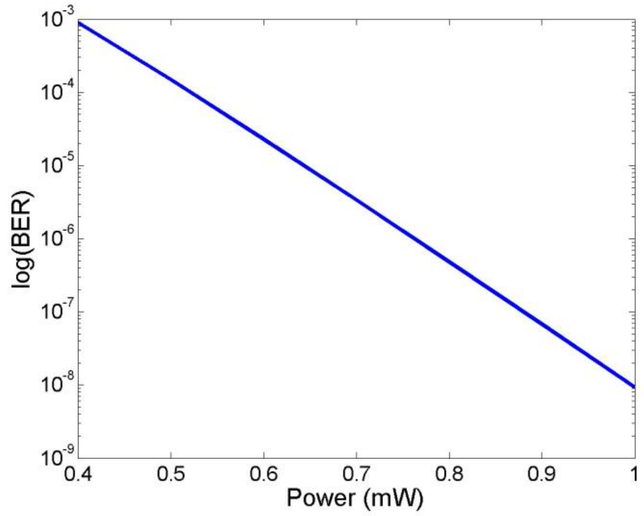


Figure 14 Indirect modulation with PIN detector and amplifier. BER vs Power. The modulator extinction ratio is 12 dB and the amplifier gain is 10 dB.

BER is 1.5e-4 dB at 0.5 mW, 4.8e-7 dB at 0.8 mW, and 9.3e-9 dB at 1 mW. Comparing to the scenario with the plasmonic amplifier, we see that the larger thermal noise of the PIN detector leads to worse BERs.

We next set the laser power at 1 mW and calculate BER vs amplifier gain at an extinction ratio of 12 dB. The result is shown in Fig. 15.

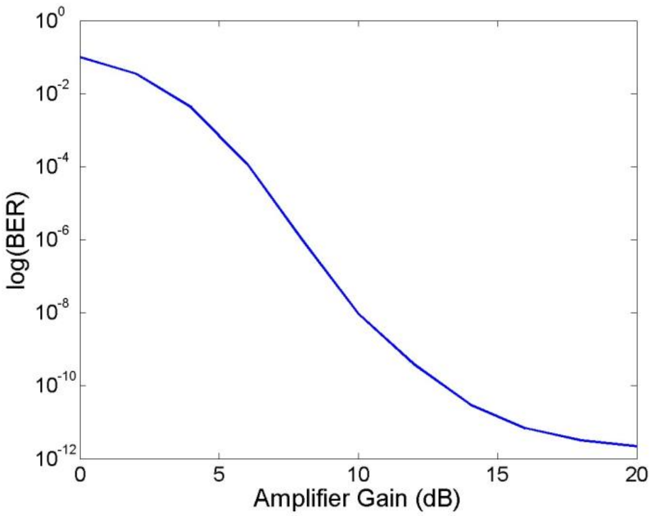


Figure 15 Indirect modulation with PIN detector and amplifier. BER vs Amplifier Gain. Laser power is 1 mW and modulator extinction ratio is 12 dB.

We see that BER < 1e-8 for amplifier gains greater than 10 dB (for ext. ratio 12 dB and laser output power of 1 mW). The curvature is due to the increased thermal noise of the PIN detector.

Next, we study the influence of the modulator extinction ratio on BER. The results are shown on Fig. 16 for a laser power of 1 mW and an amplifier gain of 10 dB.

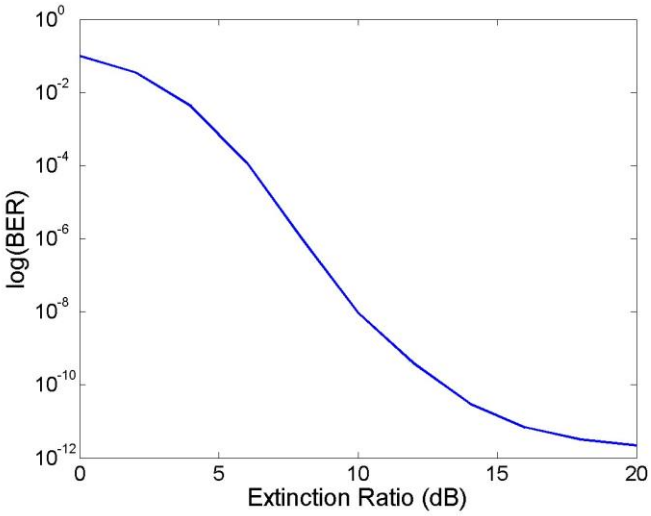
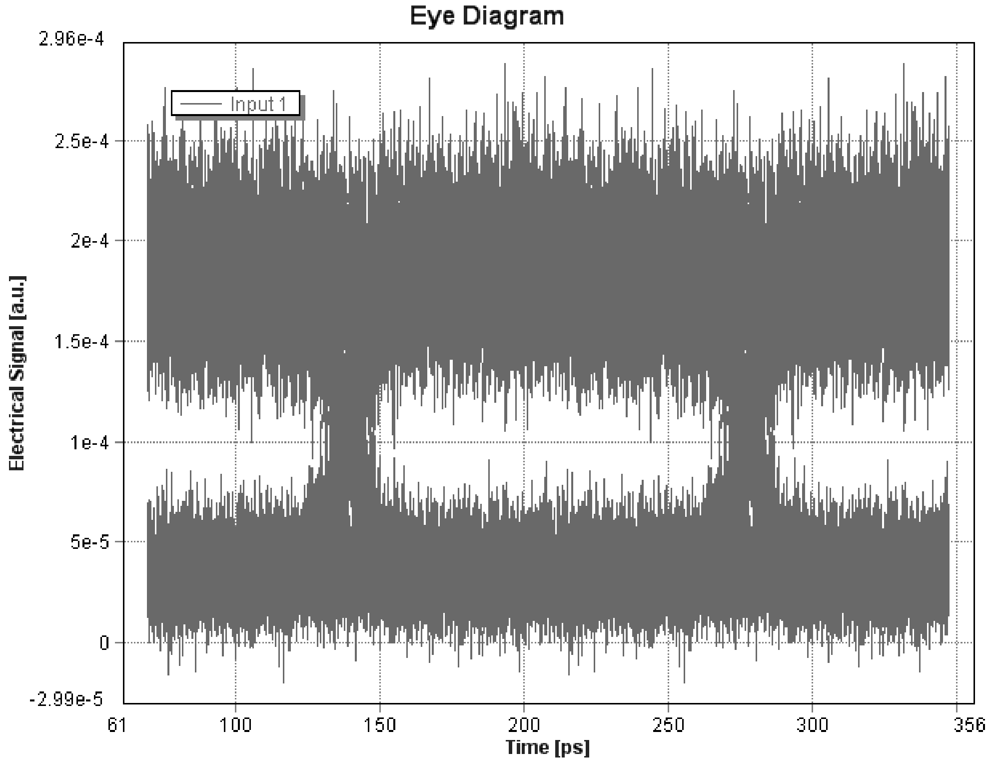


Figure 16 Indirect modulation with PIN detector and amplifier. BER vs Extinction Ratio of modulator. Laser power is 1 mW and amplifier gain is 10 dB.

Fig. 17 shows the eye diagrams for the cases with an extinction ratio of 9 and 12 dB. The respective BERs are 3.6e-6 and 9.3e-9 dB.



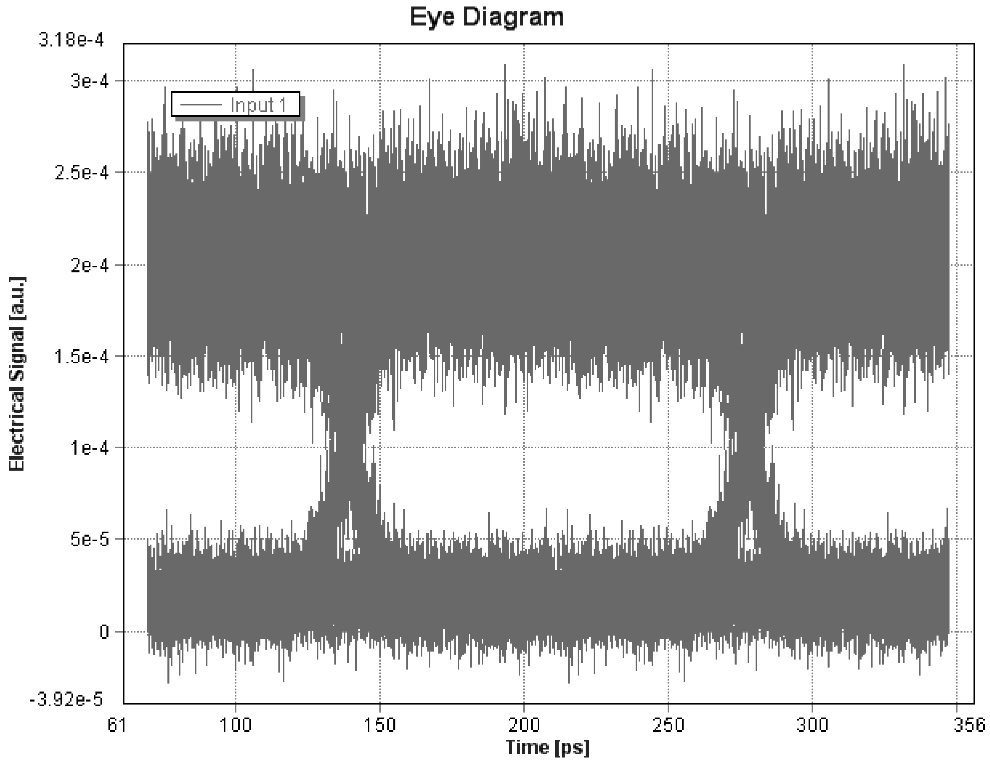


Figure 17 Indirect modulation scenario, with PIN detector and plasmonic amplifier for the same received power. Eye diagrams at a laser power of 1 mW, for an extinction ratio of 9 (upper) and 12 (bottom) dB.

Direct modulation

The main device parameters used for direct modulation simulations are the following:

Metallo-dielectric Laser: DC emission at 1550 nm, power at 50 μW (but other powers have been simulated too), bit rate 7.2 Gb/s, RZ.
Gratings: advanced gratings from IMEC with 2dB loss.
Plasmonic amplifier: Maximum output power at 0.2 W, Noise Figure 4 dB, Noise Bandwidth 25 THz. The gain goal within NAVOLCHI is 10 dB, but various gains have been simulated.
PIN Detector: Responsivity 0.5 A/W, dark current 100 nA, thermal noise 10 pA/Hz^(1/2).
Plasmonic Detector: Responsivity 0.1 A/W, dark current 1 μA, thermal noise 25 fA/Hz^(1/2).

We note that at the time of submission of this deliverable, there were no phase data (or estimations) available for the phase characteristics of the devices. We have therefore omitted such calculations. When such data is available, additional direct modulation simulations will be performed, should it be requested.

First, let's take a look at the scenario where the PIN detector is used without a plasmonic amplifier. At a laser output power of 50 μW, the BER is calculated to be 3e-9 dB. Figure 18 shows the how BER is related to the laser output power.

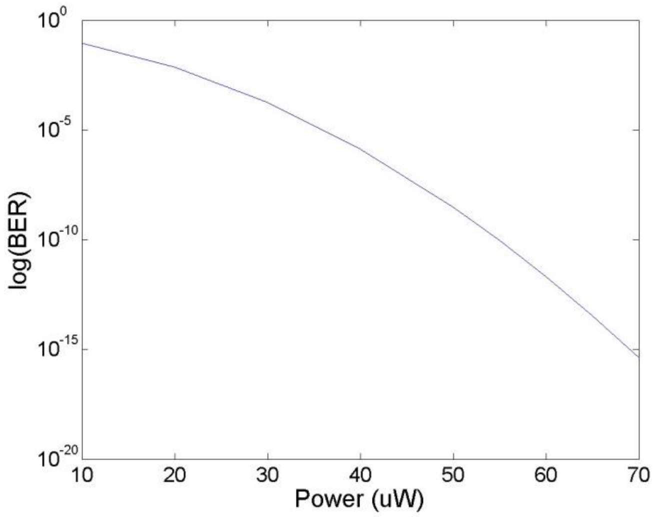


Figure 18 Scenario with direct modulation and PIN photodetector, without plasmonic amplifier. BER vs laser output power.

We see that BER < 1e-9 dB for powers > 50 μW, and vanishes for powers greater than 70 μW. The expected output power of the metallo-dielectric laser is 50 μW, and therefore appropriate for this system.

If we now add the plasmonic amplifier to the system, BER vanishes already for a gain of 3 dB. Table 2 shows BER for the gain values.

Amplifier Gain (dB)	BER (dB)
0	1.8e-6
1	2.8e-9
2	1.35e-13
>3	0

Table 2. Direct modulation with PIN detector and plasmonic amplifier. BER vs Amplifier Gain. Laser power is 50 μW.

We next turn to the case with the plasmonic detector, without an amplifier. Table 3 shows the BER vs Power calculations.

Laser Power (μW)	BER (dB)
10	5e-5
20	4.5e-13
>30	0

The metallo-dielectric laser output power (50 μW) is therefore more than enough for an error-free system.

5. Conclusions

A simulation platform has been developed with the commercial VPI Photonics software and the NAVOLCHI system has been studied. Eight different configurations have been studied in total: with direct or indirect modulation, with plasmonic or PIN detector, with or without amplifier. The Bit Error Rate has been calculated for each case, sweeping parameters such as the laser output power or the amplifier gain. In the direct modulation case the signal phase distortions have not been taken into account due to lack of chirping information for the plasmonic devices. In addition, we noted that many of the device parameters used in the simulations are estimations at this point of development.

The results for the indirect modulation case show that the estimated metallo-dielectric laser (that is being developed within NAVOLCHI) output power is too low to receive an acceptable BER at the receiver end. Powers on the order of magnitude of mW are needed for error-free transmission this case, as opposed to the 50 μW that the NAVOLCHI laser delivers.

On the other hand, in the direct modulation scenario the 50 μW of laser output power seem to be enough for error-free transmission.

In view of these results, it appears appropriate that the laser (metallo-dielectric laser) and the modulator (plasmonic modulator) that are being developed within NAVOLCHI are demonstrated separately at the end of the project. For example, separate plasmonic chip-to-chip systems can be demonstrated. In one case, the metallo-dielectric laser will be used with direct modulation at the transmitter. In a second system, the plasmonic modulator can be paired with a commercial laser at the transmitter.