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Virtual prototyping of complex photonic components and integrated circuits for polymer-based integration platform

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ABSTRACT

Recent developments in versatile polymer-based technologies and hybrid integration processes offer a flexible and cost-efficient alternative for creating very complex photonic components and integrated circuits. The fast and efficient test, optimization and verification of new ideas requires an automated and reproducible simulation and design process supporting flexible layout-driven and layout-aware schematic-driven methodologies. When considering very complex designs, even small fabrication tolerances of one building block could make a huge difference on the performance and manufacturability of the whole structure. To reduce risk of failure and to make performance predictions by virtual prototyping reliable, the simulation model of each single building block needs to be working correctly based not only on the appropriate mathematical and physical equations, but also on adequate information provided by the foundry where the final structure will be manufactured.

The PolyPhotonics Berlin consortium targets to address these design challenges and establish a new versatile integration platform combining polymer with Indium-Phosphide and thin-film filter based technologies for numerous photonics applications in the global communications and sensing market. In this paper we will present our methodologies for modeling and prototyping optical elements including hybrid coupling techniques, and compare them with characterization data obtained from measurements of fabricated devices and test structures. We will demonstrate how the seamless integration between photonic circuit and foundry knowledge enable the rapid virtual prototyping of complex photonic components and integrated circuits.

Keywords: Photonic components, integrated optics, polymer-based integration platform, polymer waveguides, Process Design Kit, simulation, design

1. INTRODUCTION

Ever-increasing demands for big data transfer, together with the trends of miniaturization of optical devices and lowering costs of optical chips are nowadays main topics of scientific research. To handle these requirements novel integration platforms need to be considered. Despite already established development of integrated Si and InP photonics technologies, costs of the design and fabrication of photonic integrated circuits (PICs) are still much higher than corresponding microelectronic devices. A very interesting solution for lowering costs was developed by the Fraunhofer Heinrich-Hertz Institute (HHI): the PolyBoard platform, which allows for hybrid integration of polymer-based photonic structures [1]. In [2], the possibility of integrating multiple functional elements into a single polymer chip was shown. PolyBoard is a low index contrast platform; the refractive index contrast between waveguide core and cladding is in the range of 0.005 and 0.030 based on materials from the ZPU12 series offered by ChemOptics Ltd. Material properties allow for low process temperatures (below 200°C) and flexible hybrid integration, which can be realized in room temperature by simple UV curing of manually inserted and aligned elements. Additionally, the high thermo-optical coefficient of the polymer material, together with low thermal conductivity, provides a huge potential for efficient thermo-optical tunable structures [3-4]. Furthermore, the PolyBoard platform allows for the integration of 3D photonic structures for parallel processing of multiple optical flows [5].

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The capabilities of the PolyBoard platform are extended in the framework of PolyPhotonics Berlin – an entrepreneurial project of enterprises and research institutes of the Berlin-Brandenburg region in Germany that aims to establish a new versatile polymer-based integration platform combined with Indium-Phosphide and thin-film filter technologies for numerous photonics applications in communications, sensing and analytics [6]. To simplify the whole process of designing and verifying complex photonic components and integrated circuits, a toolbox of simulation models representing libraries of photonic and optoelectronic building blocks is required. This will be a part of a newly developed standardized process design kit (PDK) containing generic foundry models [7-8], and integrated into modern electronic design automation (EDA) and photonic design automation (PDA) tools.

In the following section, the methodology of modeling polymer-based components is described. Then we discuss details of prototyping the basic components. This includes waveguide structures, coupling between waveguide and fiber (via U-groove), thin-film-based filters (TFF), photodiode, as well as a tunable laser, consisting of an InP gain chip, a polymer-based phase shifter and a grating. Finally, we will show an example of an integrated transceiver device on polymer chip containing all these elements in a schematic illustrated in Figure 1.

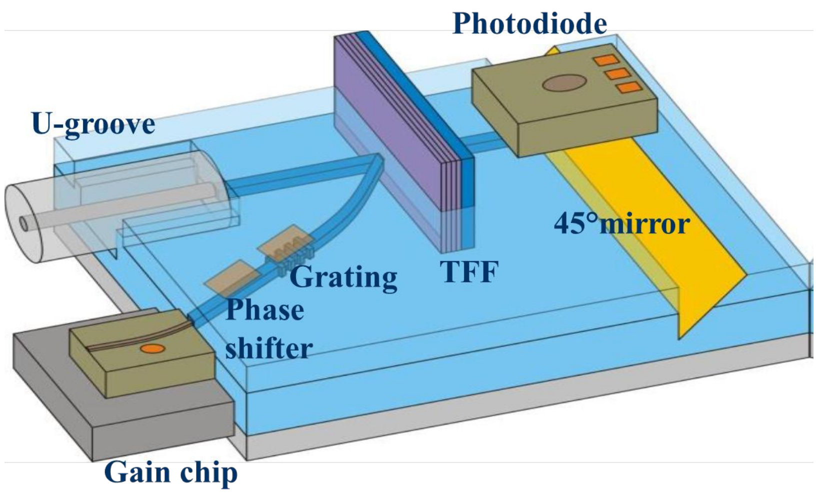

Figure 1. Schematic representation of the hybrid polymer-based tunable transceiver chip

2. METHODOLOGY

The main difference between designing photonic and electronic integrated circuits is the fact that optical waveguides in PICs play a twofold role. In some cases, they merely serve as optical connectors between two functional building blocks, similar to electrical wires in electronic circuits. In other cases, they act as functional components on their own, influencing the optical properties of the PIC, for instance due to different optical path lengths and characteristics. This problem can be addressed by considering essential characteristics of functional building blocks in photonic and optoelectronic circuit-level simulation tools. A major challenge for this is to obtain detailed information about the effective index and group mode indices. These parameters could be either obtained from measurements or calculated using device-level solvers. Considering the second option, several important values describing the waveguide cross section and refractive indices of cladding and core are to be known.

Designing realistic chips, engineers need to perform not only detailed simulations of the optical PIC performance, but also consider fabrication tolerances and technology limitations of the design. Already when running circuit-level simulations it should be known if the foundry will be able to fabricate test structures. This means that the functional behavior of the device needs to be taken into account together with all foundry restrictions. This covers not only fabrication limitations, but also correct geometry values that has been verified by the foundry. All the information should be collected and included in a single library of functional building blocks available for potential PIC designs. This allows users to simulate and optimize complex photonics circuits accurately with the knowledge that the final design could be fabricated by the dedicated foundry.

3. PROTOTYPING OF BASIC COMPONENTS

3.1 Polymer waveguides

Polymer waveguides in PolyBoard have a typical square core. The refractive index of the cladding is 1.45. Depending on the refractive index of the chosen core material four different index contrasts can be obtained: 0.005, 0.011, 0.020, and 0.030. To achieve low attenuation and proper single mode propagation in the waveguide, different cross sections need to be created for each index contrast. That means, each of these waveguides will have specific values for parameters like effective index, group delay or attenuation. For bend waveguides, the bending radius influences differently the propagation characteristics for each index contrast. Additional loss due to the impact of bending and coupling between waveguide and bend has to be taken in to account.

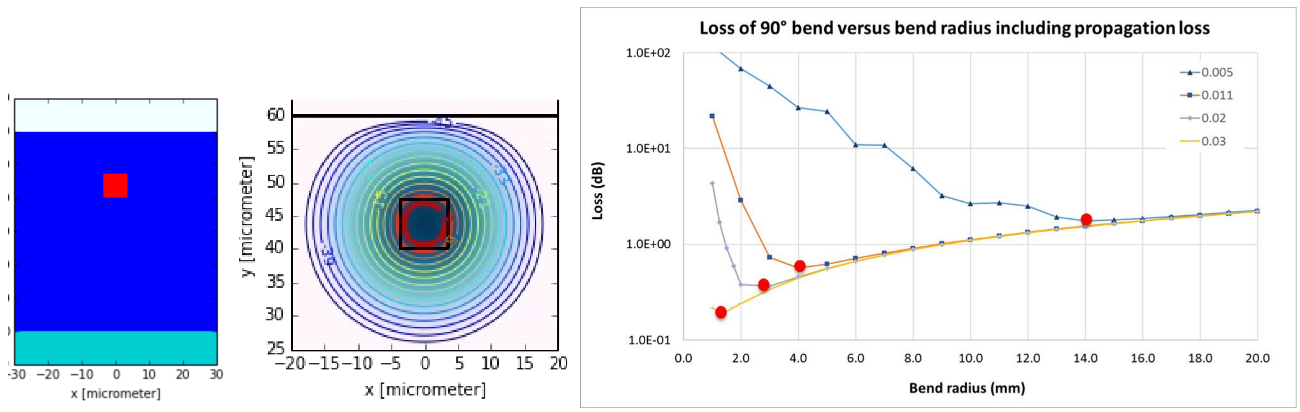

Figure 2. Waveguide cross section and mode profile for index contrast 0.005, and optimization of 90° bend waveguide (calculated with VPImodeDesigner).

All these points need to be accounted properly in the simulation model allowing the designer to apply the module that will correspond to the real, fabricated device. We performed several simulations regarding different cross sections and waveguide bends, validated them by measurements, and performed optimizations. Figure 2 and Table 1 show results of the radius optimization for 90° bend waveguides for the four available index contrasts.

Table 1. Optimization of radius for 90° bend waveguides (@ 1550 nm)

Index contrast	**Waveguide core geometry**	**Optimized radius**	**Minimum loss**
0.005	7.3 x 7.3 μm^2	14 mm	1.77 dB
0.011	6.0 x 6.0 μm^2	4 mm	0.57 dB
0.020	3.5 x 3.5 μm^2	3 mm	0.37 dB
0.030	3.2 x 3.2 μm^2	1.25 mm	0.19 dB

3.2 U-grooves for passive fiber-to-chip coupling and micro-optical elements

Another important modeling task is to optimize the coupling between fiber and waveguide. To simplify this process and the final fiber assembly, a standardized U-groove element is proposed with predefined etched area matching the fiber size. The fiber can then be inserted manually and aligned passively. Consequently, neither expensive assembly nor measurement equipment is required. The etching allows setting proper vertical and horizontal boundaries for fiber coupling, which facilitates the accurate positioning of the fiber. Fixing the fiber is realized by UV-curing of optical glue. However, U-grooves could serve for other interesting applications as demonstrated in [9] for a free space optical element. By deep etching of the polymer, it is possible to obtain a free space propagation region on chip (through air), which results in the creation of a resonator with wavelength shift.

Appropriate simulation models of these structures require the optimization of the coupling between fiber and waveguide, free space propagation between two elements, and the calculation of the additional loss due to vertical misalignment. Due to the square waveguide core geometry, the mode profile is similar to a Gaussian beam. This allows for the calculation of the free space propagation using the ABCD matrix theory [10]. Firstly, the overlap between modes of the first component and a Gaussian beam needs to be calculated. Then the beam properties after the required distance can be obtained. At the end, the beam needs to be overlapped with the modes of the next component. The optimization of this structure includes both finding the optimal waveguide width for obtaining the lowest possible coupling loss (Table 2), and tests of coupling tolerances including misalignment due to fabrication tolerances of the U-groove which could result in a vertical offset (Figure 3).

Table 2. Optimization of waveguide width for fiber coupling (@ 1550 nm) for refractive index 0.03

Waveguide width	0.5 µm	0.8 µm	1.6 µm	3.2 µm
Coupling loss	2.09 dB	0.43 dB	0.83 dB	1.62 dB

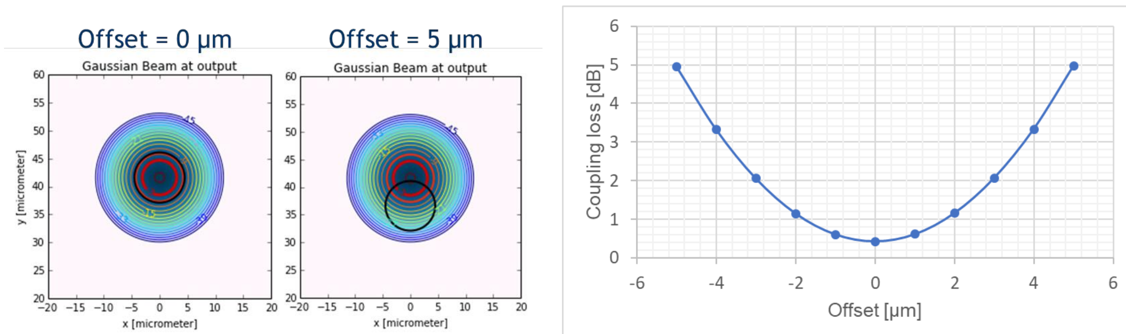

Figure 3. Schematic representation and simulation results representing fiber to waveguide coupling with vertical offset for index contrast 0.03 and waveguide core width 0.8 µm (calculated with VPImodeDesigner)

3.3 Thin-film-based filters and polarization handling elements

To perform wavelength filtering and polarization control on chip, several different functional elements are required. Wavelength filtering, as well as polarization splitting and combining, is implemented by thin-film-filters (TFF), which can be manually inserted via a prior etched slot, vertically to the polymer waveguide. Manually inserted filters are actively adjusted and fixed with UV curing glue. Due to the error that comes from manual adjustment, the transfer characteristic of these elements is extremely difficult to be modeled in all detail.

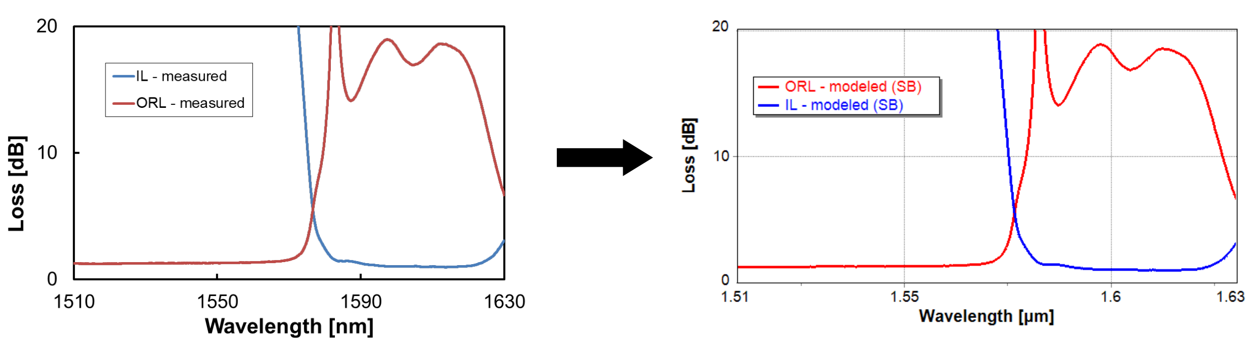

Figure 4. Measured (left) and generated simulation model (right) filter characteristic

For circuit-level simulations, a detailed analytical model calculating the superposition of all the forward and backward propagating light parts through the TFF device is not necessary. Instead, we utilize a black-box modeling approach, which is based on the overall TFF transfer characteristics in forward and backward direction. This allows one to assume that the component is perfectly inserted and aligned, as well as to account for assembling tolerances by accounting for (randomly varying) additional wavelength-dependent loss. Figure 4 shows exemplary filter characteristics in forward and backward direction.

3.4 45° mirrors for vertical coupling of photodiodes

Photodiodes are integrated on top of the chip. Coupling of output light to the photodiode is realized using a 45° mirror. The optical signal leaves the waveguide, passes through optical glue, and is reflected via the mirror into the active region of the photodiode, as shown on Figure 5. The waveguide-photodiode coupling can be modeled similarly to the U-groove coupling by applying the ABCD matrix theory. The main difference here is that the propagation path needs to be split into two parts with the 45° mirror between them. The photodiode characteristics are described by carefully adjusted parameters defining its responsivity, the amount of dark current and shot noise to model accurately the real structure. Modeling the complete building block includes both, photodiode and the coupling element. As the spacing between mirror and photodiode (d_2) is the same for each waveguide geometry, the coupling optimization depends only on the spacing between waveguide and mirror (d_1).

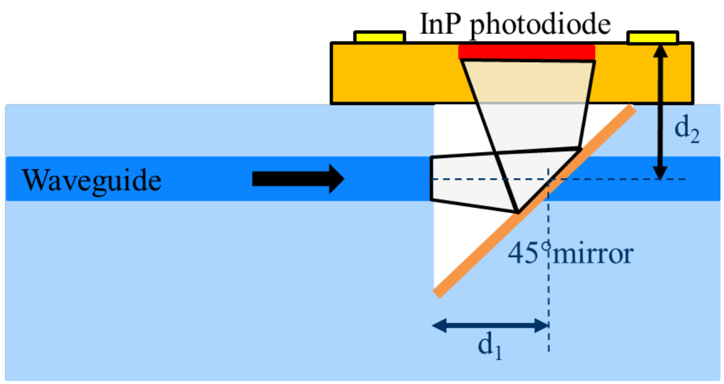

Figure 5. Schematic representation of photodiode coupling

3.5 Hybrid three section tunable laser (grating + phase shifter + gain)

A tunable laser can be created by hybrid integration with an InP gain chip. The light from the gain chip is emitted onto the polymer platform into an additional waveguide for extended cavity and passes a phase shifter before being partly reflected by a grating section. All of these elements require careful modeling. The gain chip characteristics are typically provided by the foundry directly. The phase shifter is realized as thermo-optical shifter: applying current to the electrode increases the temperature on the chip, which results in the change of effective index of the waveguide and the corresponding phase change. A similar effect is used on the Bragg grating to tune the laser emitting frequency. The Bragg grating structure is simulated using a multi-section transmission line model (TLM) [11]. Each section of the grating corresponds to one refractive index change (half of the grating period) allowing for simulating very detailed grating characteristics. As this model is very detailed and it is not necessary for the user to know all the non-volatile parameters to describe it, a simplified model is provided for end-user characterization. This simplified grating model contains only two parameters: the length of the device and the emission wavelength. All detailed parameters, including given foundry restrictions, are calculated based on them. Additionally, the coupling between the gain chip and polymer waveguide needs to be calculated. For this, the gain chip mode is represented by a Gaussian beam based on parameters provided by foundry, and is overlapped with the waveguide taper to minimize the coupling losses. Figure 6 shows an example of simulated spectra of the tunable laser for four different electrical currents applied to the grating.

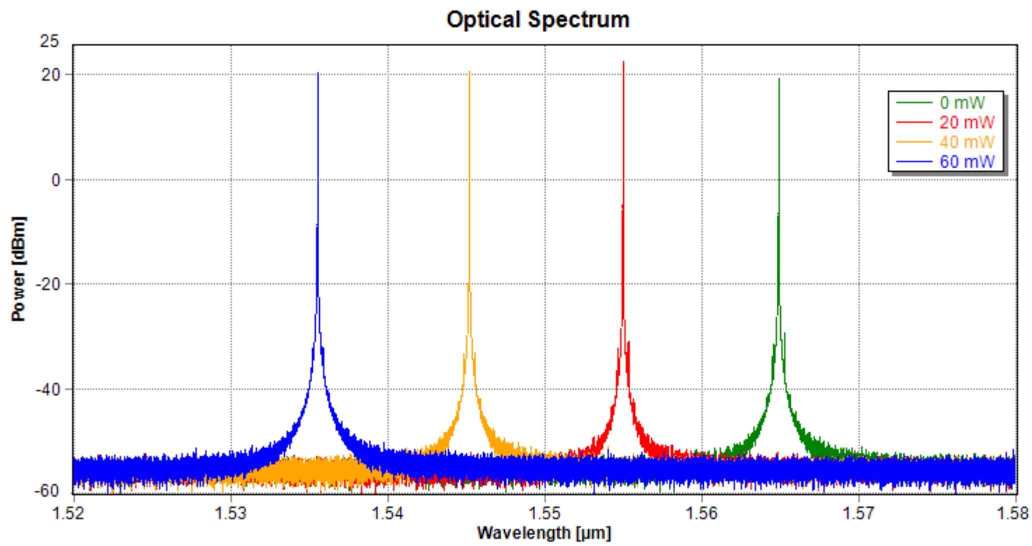

Figure 6. Optical spectra of laser tuning for different electrical power values applied to grating electrode (simulated with VPIcomponentMaker Photonic Circuits)

The tunable laser was simulated with varying parameters trying to optimize two main characteristics: wavelength tuning and side mode suppression ratio (SMSR). Our simulations, using characteristics similar to the ones of the fabricated device, show single mode lasing behavior with SMSRs of around 50 dB for the whole tuned spectrum. However, simulations show slightly higher SMSR values (Table 3).

Table 3. Measured and simulated SMSR values for different lasing wavelengths

Lasing wavelength	1.565 µm	1.555 µm	1.545 µm	1.535 µm
SMSR simulated	50.08 dB	54.11 dB	52.21 dB	52.08 dB
SMSR measured	45.38 dB	49.17	48.58 dB	not measured

We believe that the main reason for this discrepancy is due to the grating structure, which was modeled as an ideal rectangular structure. Producing a grating is a quite challenging task; the fabricated structure usually does not perfectly match with the design. To obtain a more realistic simulation model and to improve the accuracy, further investigation of the actual structure that has been fabricated is required. The simulation of laser wavelength tuning showed similar results to the measured one, published in [12]. Note, that applying an overly high current to the heater could result in burning the electrode of the real device. The current simulation model does not include a warning of this limitation as it is heavily fabrication-dependent and needs to be further investigated with the foundry.

4. HYBRID POLYMER-BASED TUNABLE TRANSCEIVER

One of the main targets of the PolyPhotonics project is to create complex functional structures for datacom/telecom applications. The idea of connecting a polymer chip with an InP gain chip and photodiode to create a fully integrated polymer-based transceiver was presented by HHI in [13]. A schematic of the fabricated device was presented on Figure 1. The simulation setup is shown on Figure 7. To prove the functionality of the transceiver, OOK modulation was applied. Optical spectra and received electrical eye diagrams for two tuning conditions are shown in Figure 8. The presented results are basis for future verification of our developed simulation models.

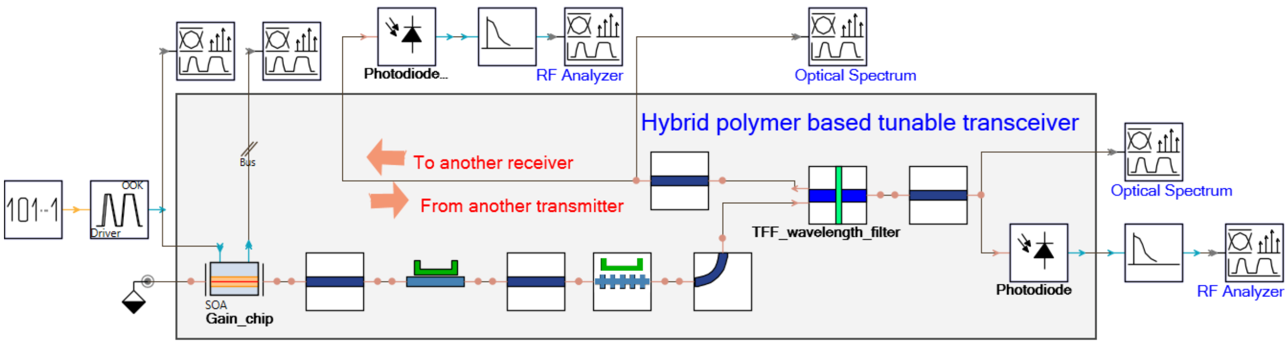

Figure 7. Simulation setup of the hybrid polymer-based tunable transceiver chip in VPIcomponentMaker Photonic Circuits

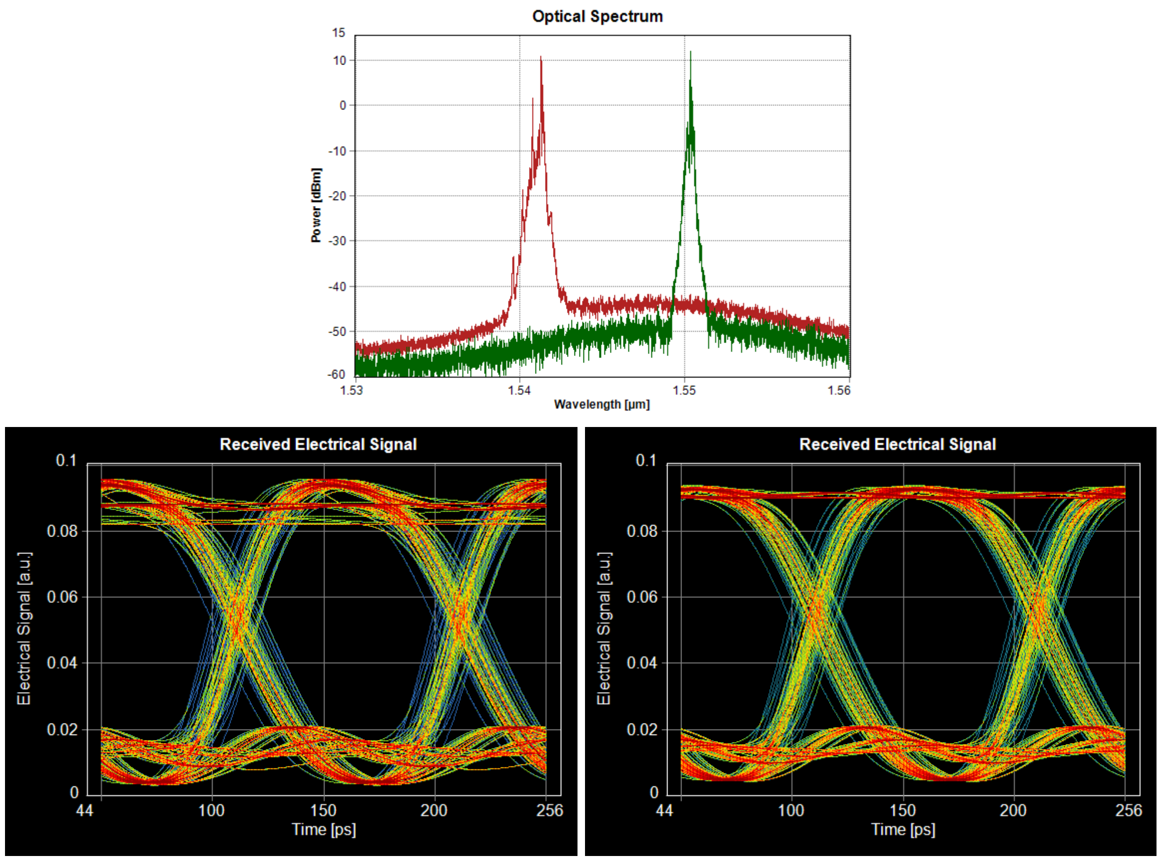

Figure 8. Simulation results for direct modulation with 10 Gb/s OOK: modulated signal spectra for two tuning conditions (top), and corresponding received electrical eye diagrams (bottom)

5. CONCLUSION

We report about our recent work performed in the PolyPhotonics Berlin consortium, which targets to establish a new versatile integration platform combining polymer with Indium-Phosphide and thin-film filter based technologies for numerous photonics applications for communications, sensing and analytics. We present our methodologies for modeling and prototyping optical elements including hybrid coupling techniques, and compare them with characterization data obtained from measurements of fabricated devices. Characterization of straight and bend waveguide, U-groove, wavelength filter, photodiode and laser elements like gain chip, phase shifter and grating have been presented. These models include not only the functionality of the dedicated element itself but also, when it is necessary, the input and output coupling. To prove the functionality of all the models an application example of an optical transceiver was presented. We demonstrated how the seamless integration of photonic circuit simulation with the foundry knowledge and experience enables the rapid and reliable virtual prototyping of complex photonic components and integrated circuits.

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