ADDAPT

Adaptive Data and Power Aware Transceivers for Optical Communications

Deliverable Report D 4.1

Concepts and specifications for adaptive optical components

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Confirmation

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Executive Summary

ADDAPT is a technology project, co-funded by the European Commission within the Seventh Framework Programme. ADDAPT aims to adapt the cable speed in the data-center to the offered dataload, by interpreting the datastream and detect the idle data in it. This report is focusing on the concepts of the adaptive optical components which are an important part of the optical cable link.

Chapter 2.1 presents an overview to the assembly concept of the demonstrator for ADDAPT which includes the optical coupling of the optical active components of special VCSEL and fast PDs to the waveguides. It is planned to use an optical near field coupling (NFC) of the optical components to the waveguide to achieve an easy coupling situation for the assembly. The design approach and the general concept for the development of fast and near field coupled VCSEL (NFL) is compiled in Chapter 2.2. In addition in chapter 2.3 there is presented the approach for a single mode VCSEL with large emitting diameter as an alternative to reach relaxed coupling conditions. Chapter 2.4 is discussing the design concept for high speed PDs and the limitations which must be considered for the NFC. The technology to manufacture the optical coupling is presented in chapter 2.5. There will be used polymer optical waveguides for a. the connection of the optical chips on one hand and b. the connection to the standard multimode optical fibers on the other hand.

1 Introduction

The primary goal of ADDAPT is to develop a high-speed electro-optical transceiver module for flexible optical links with varying performance demands and especially data rates. The Task of the WP 4 is to develop a low-cost power-efficient directly modulated surface emitting lasers (VCSELs, NFLs) and photodiodes suitable for data transmission at up to 56 Gb/s (up to 40 GHz bandwidth) and with ability to reduce data rate while simultaneously reducing the power consumption. Advanced techniques for light in-/out-coupling even at small apertures should allow smaller pitch size, lower costs and higher density of the transceiver module. A special optical near field coupling scheme will be evaluated for the easy optical coupling of the VCSEL to the waveguide and the waveguide to the PD. Therefore a new type of near field laser (NFL) and near field PD will be created.

The VCSELs and PDs will be developed and designed by VIS in cooperation with CSTG. The fabrication is conducted by CSTG. The optical fiber coupling element will be designed and manufactured by IBM.

2 Concepts and specifications for adaptive optical components

2.1 *General concept for the optical coupling and interconnect of the demonstrator*

Optical coupling and accurate alignment of high-speed optical devices to optical waveguides is a critical challenge and essentially defines the cost and form factor of optical links. In ADDAPT, a novel simple and efficient near field coupling (NFC) will be investigated as alternative to standard solutions. The NFC is reached by a close contact of the optical component like VCSEL or PD with the waveguide. No imaging with any lens is required but it is necessary to reach the close contact between the components. That must be considered in the general packaging concept of the demonstrator which is already described and discussed in the report of deliverable D6.1.

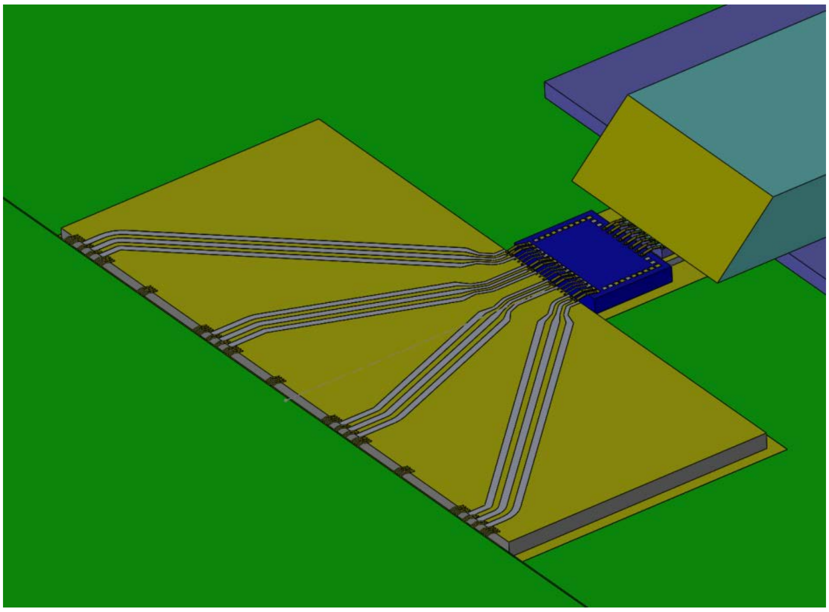


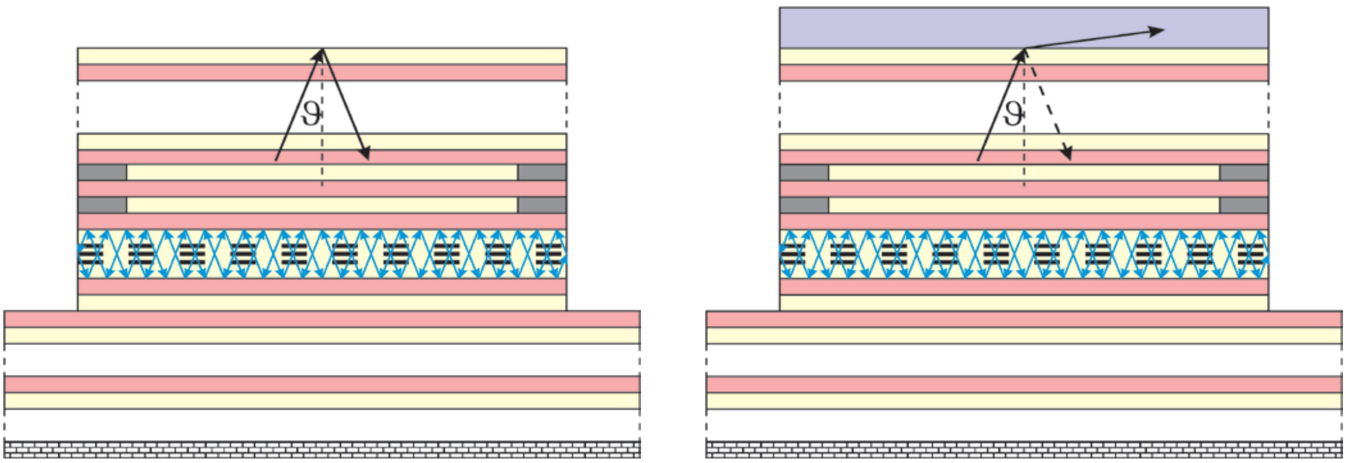
Figure 1: Central part of the demonstrator 4x56 Gb/s

The approach for the optical coupling in the ADDAPT project is to assemble the optical component to the ICs in very close distance in an up-side-up configuration. The very short wirebonds are arranged at one side of the chip and the optical waveguide component is assembled from the other side of the optical chip. The waveguide will partly overlap the optical component and will provide a close connection of the surface of the optical active area to the waveguide.

2.2 *VCSEL for optical near field coupling*

In the NFC the optical beam is coupled nearly parallel to the surface of the waveguide. The standard VCSEL is emitting perpendicular to the chip surface in some angle of about ±15°. Therefore for the NFC must be developed a special design of a VCSEL which can emit an optical beam nearly parallel to the surface into the waveguide.

The concept is to design a VCSEL resonator with an internal total reflection of most of the power when it is operated in air (with refractive index n = 1). The cavity modes with most of the power in the VCSEL have a quite large internal angle. If there is attached some material with n=1.5 to the top surface of the VCSEL than the total internal reflection turns to an evanescent field or near field which emits about parallel to the axial surface of the waveguide and therefore is coupled into the waveguide (see Fig. 2). Since the VCSEL consists of GaAs material with a refractive index of about n=3.4 this internal angle δ can be calculated to δ = 17° - 26°.



$$\vartheta > \sin^{-1}\left(\frac{1}{n_{GaAs}}\right) \qquad \vartheta < \sin^{-1}\left(\frac{n_{fiber}}{n_{GaAs}}\right)$$

Figure 2: Principle of near field coupling

Basic design for a Near Field Laser (NFL):

The general design of the VCSEL resonator (cavity) consists of 2 Bragg mirror stacks and the active layer (see Fig. 2). More than 100 epitaxial layers are defining a certain wavelength for the vertical radiation. In the center part of the vertical structure there is located the region with the optical active layer which is converting the electrical power to optical radiation and is providing the optical gain. The characteristic and the wavelength of the optical gain peak are defined by the special material composition of the active layer.

If the radiation is tilted relative to the vertical axis of the resonator there is a change in the transmission wavelength (red line in example of Figure 3). Therefore a certain angle of the radiation in the optical cavity can be selected by choosing a certain wavelength range. Since the optical gain peak of the NFL is defined by optical active layer you can select certain radiation angle by setting the gain peak to the wavelength of interest (see Fig. 3).

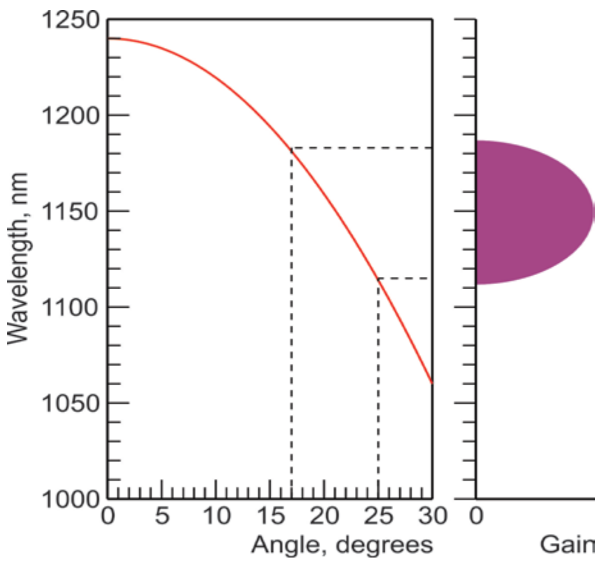


Figure 3: Selecting tilted mode by gain wavelength

Our approach for the design of a VCSEL is based on the fact that, opposite to simplified considerations, irrespectively of the refractive index of the surrounding medium the VCSEL transverse optical modes can be coupled to the modes of the surrounding medium and can leak there. Let us assume that the VCSEL layer structure incorporates a second cavity resonant at a significantly longer wavelength in comparison to the VCSEL mode for the normal propagation of light. The second cavity mode, however, at some tilt angle becomes wavelength resonant to the active cavity mode as shown in Fig. 4. In case these modes belong to different parts of the structure (the core and the periphery) the leakage of the VCSEL mode into the tilted second cavity mode of the periphery is principally possible. The tilt angle of the second mode refers to the leakage angle of the VCSEL cavity mode.

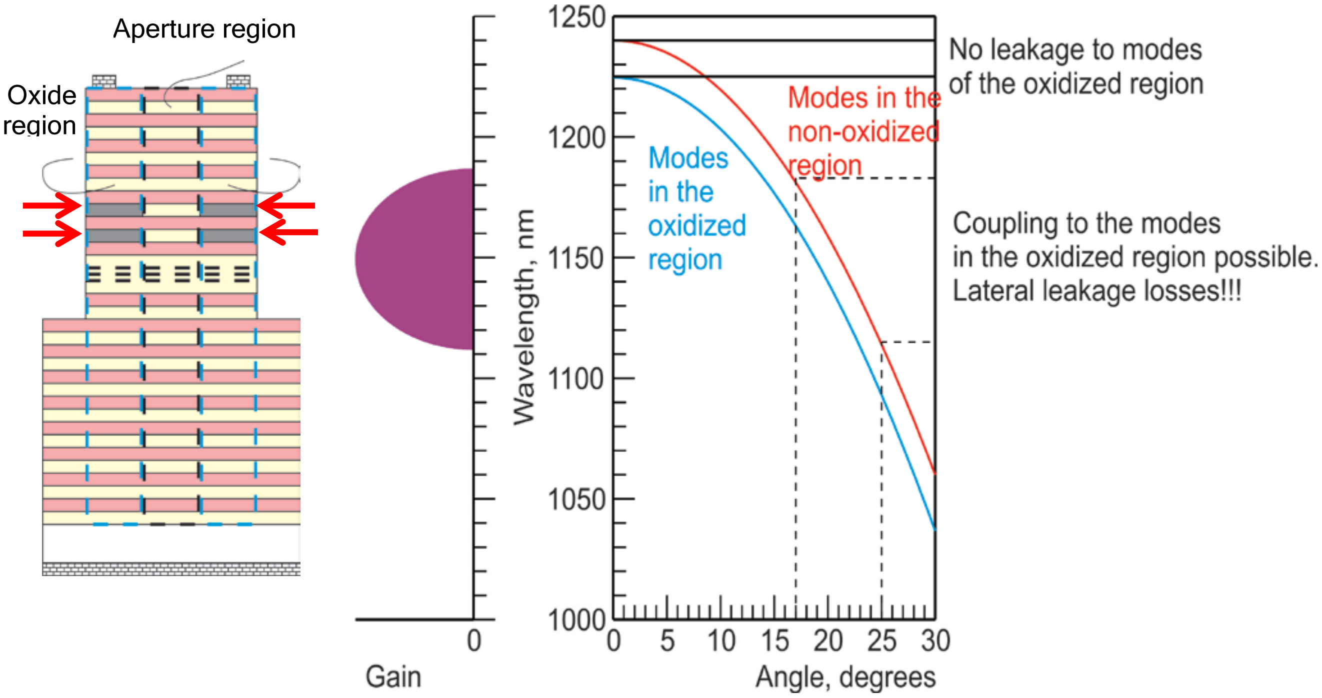


Figure 4: Leakage losses of tilted modes in VCSEL

Although the oxidation of the aperture layers lowers their refractive index, the effect of the oxidation on the vertical profile of the optical mode is rather small. The profiles of the optical mode in the core and in the oxidized periphery match very well match providing a strong leakage of the optical modes to the periphery. The VCSEL optical mode exhibits only a very low reflectivity in the lateral plane (~4%).

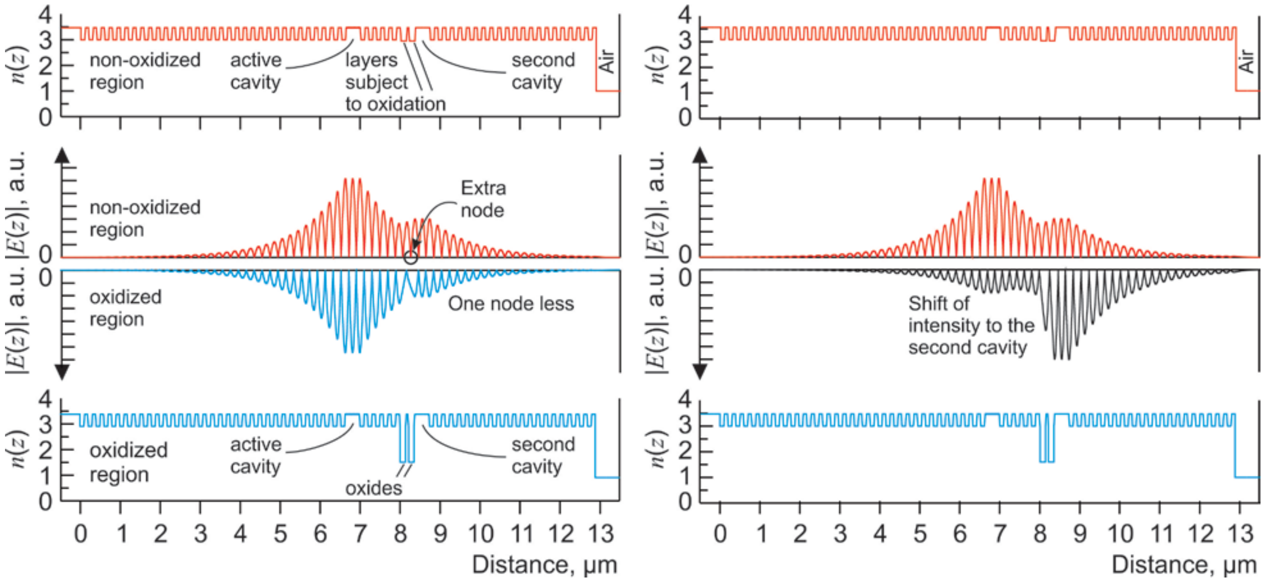


Figure 5: Prohibiting coupling to modes of oxidized region

To reduce leakage of the tilted modes in the lateral plane and to provide an efficient confinement of the mode in the core region, a duo cavity VCSEL was designed and fabricated. The two cavities are slightly off–resonance. The VCSEL optical mode in the core is shown by a red profile in Fig. 5. Due to a duo cavity design, each of the two optical modes at the oxidized periphery has a profile which is very different from the profile in the core region. The mode at the periphery having the intensity maximum in the active cavity (blue curve) has one node less than the VCSEL mode in the core region leading to a phase reversal. The other mode has the intensity maximum in the second cavity. Therefore the matching of each of the two modes at the periphery with the VCSEL mode in the core is significantly reduced. The effective reflectivity of the VCSEL mode in the core is estimated to about 40–50% demonstrating a significantly enhanced confinement of the optical mode in the non–oxidized core region.

For the production of NFL in general there will be no special additional production processes compared to the manufacturing of standard VCSEL. That is important to reach a low cost design.

A first prototype with characteristics of a near field laser has been fabricated and is ready for a transfer to the project partners for first angular resolved optical coupling experiments.

The basic characteristics of a NFL should be very similar to a standard high speed VCSEL. Table 1 compiles some estimates for the device.

Table 1: Basic specification of the NF-VCSEL

Parameter	Unit	Value
Threshold current	mA	1
Differential efficiency	W/A	0.3 – 0.5
Differential resistance	Ω	100 – 130
Resonance frequency	GHz	20
3dB frequency	GHz	20-25
Junction capacitance	fF	130
Active region resistance	Ω	100

2.3 *Single Mode VCSEL as fall back solution*

The motivation of NF laser is to simplify the coupling to narrow waveguides. The concept of the NF coupling of waveguides was demonstrated by IBM in the beginning of 2000ies. The very first devices for tests with NFC are made available by VIS.

However, a complete high speed link has never been realized with such coupling before and this issue may result in high risk. Thus, there should be a fallback solution which is on one side simplified coupling to narrow waveguides (small pitch size like in the case of multicore fiber, better coupling tolerances). This can be achieved by applying large aperture (~5 µm) single mode VCSEL which on one side matches the standard coupling scheme and on the other side allows a predictable far field and thus improved coupling tolerances. Another advantage is longer transmission distance. Therefore, VIS will develop as a fall back solution a VCSEL with vertical emission for a standard coupling scheme but with single mode emission. The background for that feature is the characteristic of the latest MMF.

For the transmission with very high speeds various advanced types of MMF with 50µm-graded index fiber core were developed: OM2, OM3 and OM4 with an Effective Modal Bandwidth (EMB) exceeding 4700 MHz*km. This specification is reached by the reduction and tight control of the modal dispersion of the MMF. But there is already present the chromatic dispersion of the MMF which is caused by the wavelength dependence of material parameters. On these OM4 fibers the transmission distance at a speed of 25 Gb/s is limited to an important fraction by this chromatic dispersion of the MMF. This limitation can be overcome by a reduction of the optical spectral width of the transmitter.

There are several challenges to get a good single mode VCSEL: The optical output power of 1 mW should be reached without extremely high current density which may result in a fast degradation of the device. Further, to get a reasonable side mode suppression ratio (SMSR) of about 20 dB a good mode control needs to be implemented.

The concept to reach a good single mode performance is to introduce well defined mode selection into the resonator design of the VCSEL by the proper oxide-aperture design. It is possible to realize both, the necessary power level >1mW and the relative low resistance (~100 Ω) to match the standard electronics.

2.4 *High speed photodiode*

Most critical feature of a receiver is the reach of high speed response in combination with high responsivity and low dark current which can be well reached by a PIN detector. A planar PIN detector may absorb radiation even outside of the active region. Carriers are created which can diffuse slowly to the depletion region and may create a slow tail of the fast signals. Therefore, there is selected a GaAs PIN detector with a mesa structure on a semi-isolating (S.I.) substrate as basic design (see Fig. 6).

With such a design it is possible to reach a very low parasitic pad capacitance, low dark current and high responsivity. The basic vertical material structure of such device is presented in Table 2.

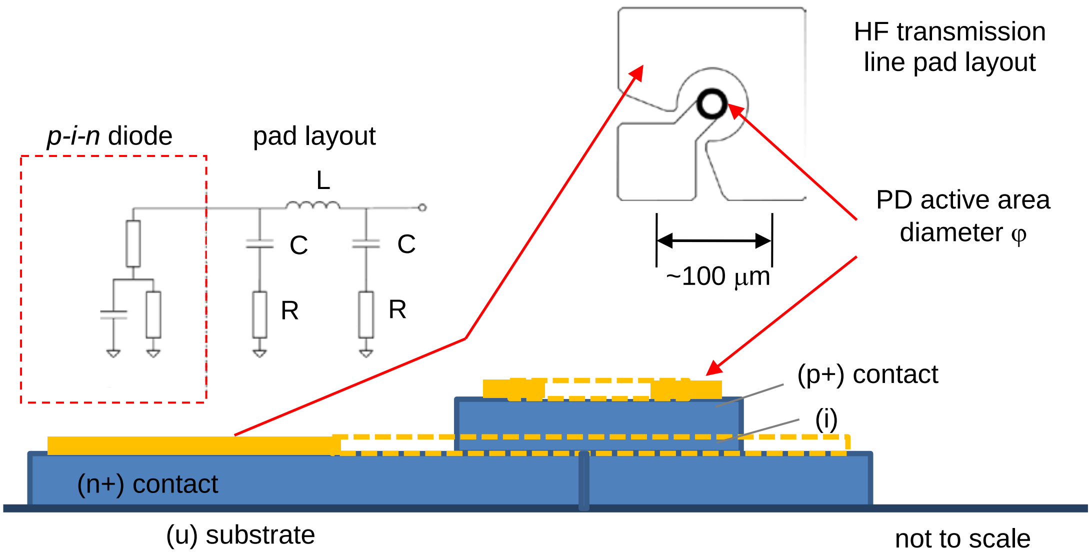


Figure 6: Basic design of fast photodiode

Table 2: Material structure of photodiode

	Material	Type
Cap layer	GaAs	p^+
Contact window	$Al_{0,3}Ga_{0,7}As$	p^+
Absorption layer	GaAs	u/d
Contact layer	GaAs	n^+
Substrate	GaAs	S.I.

The overall bandwidth of such a device is limited by the overall electrical capacity which consists of the device capacitance as well as the parasitic pad capacitance. The device capacitance can be reduced by reducing the active diameter of the device. Further, the thickness of the undoped absorption layer will influence the bandwidth of the PD.

The active diameter of the PD should be as large as possible to reach an easy optical coupling to the device. On the other hand the diameter must be reduced to reach an acceptable bandwidth. Therefore, it is necessary to tailor an optimized device for each application. In the ADDAPT project we will try to optimize the bandwidth by enlarging the thickness of the undoped absorption layer. There will be a trade-off of the carrier transit time versus reduction of the capacitance which has to be optimized but it is expected that the acceptable diameter of the active area is around 20-25 µm to reach the necessary bandwidth of 40 GHz or beyond. Such device will have a capacity of about 100-130 fF which should be acceptable in this application [1].

Near Field Coupling of waveguide to fast PD:

There were several discussions of possibilities of a NFC from the waveguide to the PD in the first project phase. The crucial fact for such a coupling is the very small size of the sensitive area of the PD. Typical waveguides in short distance datacom applications are multimode and have cross sections of about 30 – 50 µm. The high speed PD must have a smaller diameter than these dimensions. In the past there was demonstrated the NFC of waveguides or lasers to waveguides or as adiabatic coupling with a kind of waveguide taper on one side [2]. All these examples need some longer coupling length to reach an efficient NFC. Since the size of the high speed PD cannot be enlarged for such coupling the coupling efficiency can be very low. The concept for the development is to perform first the critical optical coupling test with the first near field lasers. If these laser tests are successful then there will be a special near field PD design applied to the receiver of ADDAPT. At this stage a standard coupling with lens or with direct waveguide connection (maybe with a taper) will be applied.

2.5 *Optical coupling unit with waveguides*

For interfacing the high speed VCSEL with a fiber, we will explore several solutions. A novel concept based on optical near field coupling will be investigated as an alternative to established butt coupling or lensed coupling schemes. In the near field coupling approach, the modal field in the VCSEL is evanescently coupled to a waveguide brought in contact with the VCSEL surface as depicted in Fig. 7 below.

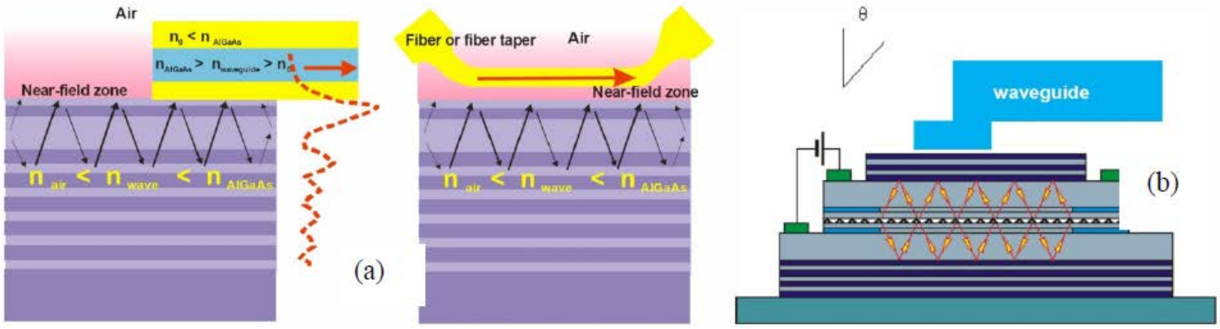


Figure 7: Schematic representation of a near field coupling device (a) and a near field coupled laser (b). From the DoW.

Critical to the success of this concept is the close integration of the external core waveguide. Polymer waveguide technology offers an ideal means to realise such a scheme. The discrete processing of the cladding and core layers provide the opportunity to locally open the waveguide core. IBM has been investigating such a polymer waveguide technology since several years. Both the polymer waveguide technology, as well as waveguide to fiber connector solutions were established [3]. In ADDAPT we will build on this expertise to demonstrate the feasibility of the near field coupling approach for VCSEL to polymer waveguide coupling. In this report we review the state of the art in the polymer waveguide technology as established at IBM.

A polymer waveguide structure is build up from two a cladding and a core, similar to a fiber. Both materials are transparent at the wavelength range of interest; the core layer has a slightly higher refractive index to guide the light. The materials we work with are UV curable. First, the cladding layer is deposited onto a flexible or rigid substrate and cured through a flood exposure to form a uniform layer. Subsequently, the core layer is deposited and locally exposed through direct laser writing or by mask exposure. The non-exposed material is washed away in a development step. Subsequently, the top cladding is deposited and cured. In case a local opening of the core layer is required, also here a mask exposure will be applied.

Figure 8: Several polymer waveguide structures; a spiral for propagation loss measurements (left), red light propagating through the spiral (middle) and a flexible polymer waveguide sheet (right).

For multimode waveguide structures operating at a wavelength of 850 nm, the waveguide height and width are in the range of 35 µm to 50 µm. The polymer waveguide material is based on silicones provided by Dow Corning, providing excellent optical, adhesion and stability properties.

The fundamental advantage of a polymer waveguide technology is that it represents the optical alternative to established electrical printed circuit board technology. Hence, it provides a means to not only distribute optical signals but also to provide large channel count interfacing between a transceiver chip and the system. Consequently, the interfacing from and to the polymer waveguides is a critical aspect of the technology. For ADDAPT, we focus on the waveguide to fiber connectivity. Here, we describe some of the background work demonstrated in this area. The picture below on the left shows an optical printed circuit board with embedded waveguides.

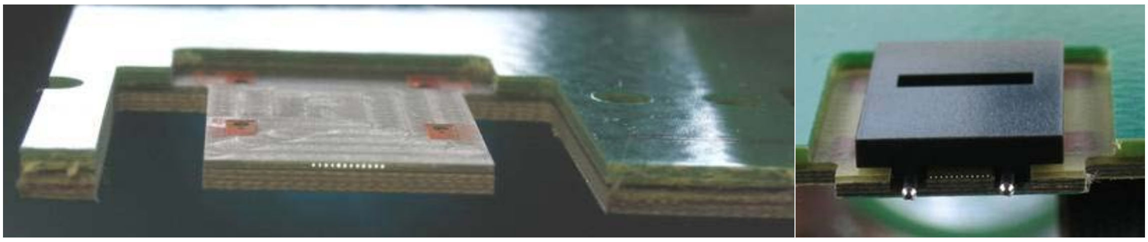


Figure 9: Printed circuit board with embedded waveguides and mechanical alignment structures (left) and after attached an MT-ferrule (right).

The alignment of a fiber array to these waveguides has to occur with a tolerance of less than 5 µm. In this case, we use copper fiducials as defined on the substrate to align the waveguides and to establish the mechanical alignment structures. After the lamination of the complete printed circuit board stack, a milling process is applied to open the stack down to the waveguide layer. Subsequently, a laser ablation process is applied to open the copper structures and form the mechanical alignment features. Here we use the reflectivity of the copper, which prevents the ablation in areas where is copper is present. In other areas the ablation goes into the organic substrate carrying the waveguides so forming a vertical reference (the copper plane) and lateral reference features (the ablated edges defined by the copper structures).

The details of the ADDAPT demonstrator will be defined in the coming months. Based on simulations, the waveguide processing and connectorization experience, we will evaluate the options in more detail and make choices on the demonstrator layout.

3 Conclusion

In this first project phase there were discussed several approaches for the optical components to reach an NFC. There must be considered several critical issues to reach an easy to align and effective optical coupling for the final solution with NFC. For this final overall approach there are necessary further simulations of the coupling situation for the transmitter as well as the receiver independently. Therefore the final coupling scheme for the demonstrator must be developed in collaboration of all component partners in the next phase.

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Acronyms

Acronym	Definition
EMB	Effective Modal Bandwidth
HF	High frequency/very high frequency
MMF	Multi- mode fiber
NFC	Near-field coupling
NFL	Near Field Laser
PD	Photodiode
SMSR	Side Mode Suppression Ratio
VCSEL	Vertical Cavity Surface Emitting Laser