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Optical Polymer Waveguides

From the Design to the Final 3D-Opto Mechatronic Integrated Device

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Preface

To keep pace with the high demand of bandwidth to transmit increasing amounts of data even in real time, many applications are heading from metal-based transmission lines to optical waveguides. As optical glass fiber technologies are the backbone of our digital infrastructure covering long-haul transmission tasks, polymer optical fibers are used for short-range transmission. By providing a multitude of advantages like less weight, higher energy efficiency at increasing data rates and smaller dimensions of devices, the demand for new developments in optical assembly and interconnection technology is increasing. This book presents a novel approach to short-range optical communication based on the functionalization of three-dimensional structures with polymer optical waveguides to build up an optical transmission line.

This research report covers methods and technologies for the design, manufacturing and simulation of three-dimensional optically functionalized mechatronic components (3D-opto-MID). This includes

- computer-aided methods for the design and simulation of 3D-opto-MIDs
- a printing process to condition the substrates for the subsequent application of optical waveguides
- the technology for manufacturing optical waveguides on 3D-formed surfaces via Aerosol Jet Printing in order to build up polymer optical waveguides, which are able to transmit signals on a three-dimensional component
- a passive concept of coupling for a subsequent division of the optical signals along the optical path of the optical waveguides during field mounting
- and a concept of coupling for the direct connection of optoelectronic converter components to the optical waveguides.

Hence the book addresses scientists, engineers, students and interested non-experts to expand their knowledge with a new approach for the realization of optical networks and opens up new solutions to implement optically integrated and highly functionalized devices.

The research results presented in this book were obtained within the interdisciplinary research group Optical Design and Interconnection Technology for Assembly-Integrated Bus Systems (FOR 1660 OPTAVER) funded by the German Research Foundation (DFG). The work was carried out by a group of talented researchers, who are all experts in their scientific fields and have successfully utilized their abilities and ideas to make a long-lasting impact on the key technology field of short-range optical transmission. We are very proud to be able to connect the design and simulation as part of the CAD-CAM chain to design optically functionalized components with the actual manufacturing processes. This optical integration increases the functional density of these devices by replacing dedicated hardware like polymer optical fibers and allows us to present a holistic approach to 3D-opto-MID for the first time.

On behalf of all researchers contributing to this book, I would like to thank the DFG for the opportunity to conduct this highly innovative research. With the conducted investigations, our research group OPTAVER was able to answer how polymer optical waveguides can be applied to three-dimensional structural components. This extends the functionality of mechatronic integrated devices (MID) by optical means, which opens up a multitude of new applications in the field of optical transmission and sensing.

Erlangen
February 2022

Professor Dr.-Ing. Jörg Franke

Contents

Current Development in the Field of Optical Short-Range Interconnects

1

Lukas Lorenz and Karlheinz Bock

1.1 Advantages of Optical Communication

The current development in the field of information and data transmission is driven by a constantly growing amount of data generated worldwide. Current predictions range from 33 Zettabytes (ZB) in 2018 to 175 ZB in 2025 [1]. The reason for this enormous growth is the increasing network of devices that traditionally have no connection to a network. In this case, we speak of the Internet of Things (IoT). This affects all areas: mobile systems, transportation, sensor technology, cloud applications, medical devices and big data systems, to name just a few [2].

The consequence of the enormous increase in generated data is the demand for increasingly higher data transfer rates to handle, transmit and store these large amounts of data. While current CMOS circuits reach higher and higher speeds, the electrical connections can hardly support them [3]. Therefore, parallel point-to-point connections with enormous space requirements are becoming increasingly popular (e.g., Peripheral Component Interconnect (PCI) Express in home computers) [4, 5]. In the near future, traditional electrical connections will reach their limits. Here photonics offers promising alternatives. This is particularly evident when comparing energy efficiency and space requirements [3], as shown in Table 1.1. These values illustrate the advantages of optical over electrical connections. Furthermore, photonic systems are insensitive to electromagnetic interference and can therefore be used in electromagnetic compatibility (EMC) critical areas.

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Table 1.1 Comparison between electrical and optical data transmission

	Electrical	Optical	Conclusion
Energy efficiency at 20 Gbit/s [3, 6]	(30…40) mW/Gbit/s	17.5 mW/Gbit/s	At high data rates, optical transmission is more energy efficient.
Space requirement [6]	3.2 mm²	0.6 mm²	ICs connected with optics need less space than the electrical pendants
Footprint for a 10 Gbit/s connector with 144 channels [7]	1620 mm²	236 mm²	Optical channels can have a smaller pitch than electrical ones

According to prognoses, the advantages in these aspects will lead to optical multimode short-range interconnects to be the backbone of upcoming IoT and Industry 4.0 applications [8]. Furthermore, they will be decisive for the further development of these systems [2]. An example of such a system is shown in Fig. 1.1. Emerging autonomous driving applications require the processing and dissemination of large amounts of data (up to 4 TB per hour [9]). This could be done efficiently, quickly and with little space requirements in the vehicle via an optical bus system.

A look at the existing solutions for optical interconnects and bus systems reveals that components for optical integration are well developed [4]. For both transmitters [11, 12] and receivers [13, 14], established technologies can be used. In addition, in the field of classical packaging and interconnection technology, solutions are already available and optical systems are established:

- Telecommunications (transmission between locations)
- Data communication (transmission between individual computers)
- Computer communication (transmission within a computer).

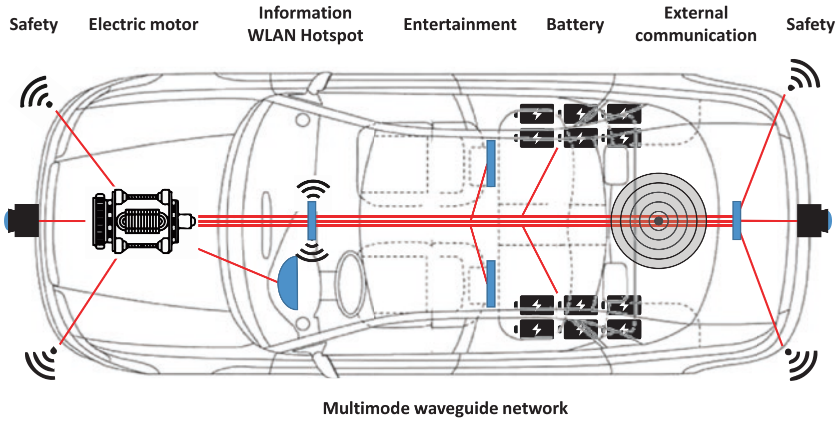


Fig. 1.1 Optical interconnects as backbone of the communication system in a car [10]

For longer transmission distances in the kilometer and longer meter range (telecommunications), optical transmission is already standard for many years. Optical solutions are also established in the area of active optical cables for rack-to-rack links in data centers (data communication) [15] and at board level (computer communication) [16, 17]. Furthermore, approaches for optical connections on the chip are already known (computer communication) [18].

However, the solutions for data communication or computer communication are all designed for use in classic IT environments, i.e., in server farms, on printed circuit boards (PCB), etc. For the emerging applications in the area of Internet of Things and Industry 4.0, it is necessary to carry out a paradigm shift and discuss new solutions. For this purpose, Lorenz [10, 19] focussed on a newly emerging application area: the device communication. This area includes applications outside the classical computer architecture. Although these applications have a connection to the Internet, the focus is on the connection and networking of modules in closed, embedded systems with connection lengths between 0.1 m and 100 m. These connections do not use classical cabling or wiring on a substrate, but embedded links in the structures—just like the system itself. The new demand for device communication also results in challenges in the design of 3D opto-mechatronic integrated devices (3D-Opto-MID [20]). The three most important challenges, which are addressed in this book, are summarized in Table 1.2.

An example of an application is illustrated in Fig. 1.2. It shows a sensor network in an airplane wing, where several modules are connected to an embedded waveguide via bus coupling. Since this is a lightning strike and EMC-critical environment, optical systems are particularly preferred.

Another example, depicted in Fig. 1.3, shows an optical strain sensor for car batteries. Since there is a need for galvanic isolation, optical sensors or at least optical connections are necessary. The waveguides are either directly applied on the battery housing (e.g., additively) or flexible foils are fixed, following the three-dimensional shape.

Table 1.2 Demands and challenges induced by upcoming applications in the device communication [10] and the chapters they are addressed in

Demand	Technical challenge	Associated chapter
Device integrated, large waveguide networks (e.g. in cars or airplanes) on structural elements	Fabrication of waveguides on 3D surfaces, which are not length limited	4 (Conditioning of Substrates) 5 (Waveguide Manufacturing)
Bus coupling of 3D-Opto-MID modules in large optical networks to avoid a huge cable harness	Coupling of waveguides without interruption, as well as asymmetric coupling ratios depending on the coupling direction	6 (Coupling)
3D-Opto-MID assemblies in compact design (e.g. as components in a sensor network)	Design, simulation and fabrication of optical networks in 3D with sufficient heat management	2 (Design) 3 (Simulation) 6 (Fabrication)

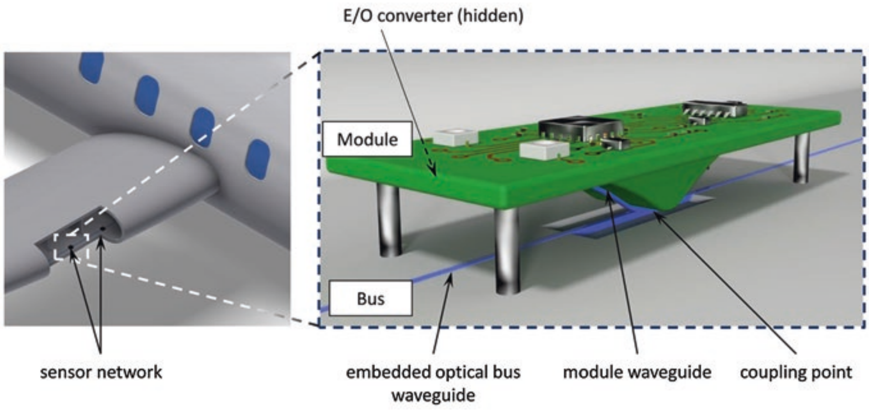


Fig. 1.2 Example application for a sensor network, which communicates via an embedded optical bus [10]

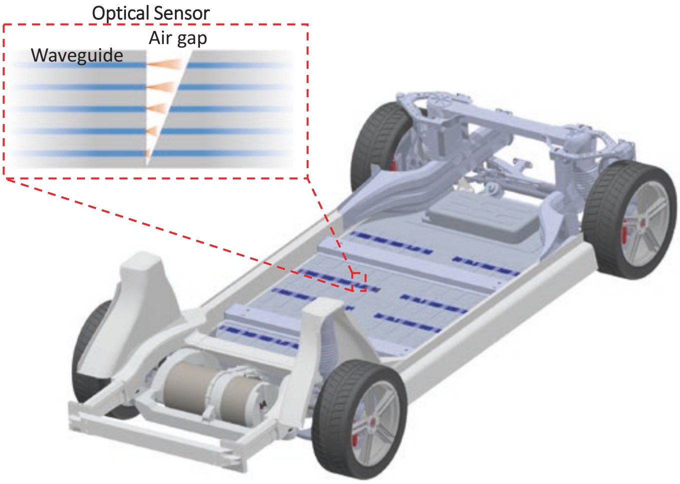


Fig. 1.3 Example for an optical strain sensor monitoring the battery health in an electric car

1.2 3D-Opto-MID for Optical Bus Systems

There are only inadequate solutions for the above-mentioned challenges. The following subchapter gives an introduction of optical short-range connections, optical bus systems and 3D-Opto-MID. The corresponding main chapters discuss then the detailed state of the art.

1.2.1 Short-range optical waveguides networks

As already described in Sect. 1.1, in the communication technology a differentiation is made between the individual connection levels, which essentially depend on the length of the optical transmission.

For telecommunications, which covers long-distance transmission, single mode fibers and wavelengths of $\lambda = 1300$ nm and $\lambda = 1550$ nm are used, which ensure low attenuation and high signal quality over long distances. However, due to the small core diameters of single mode fibers, packaging is very challenging because of the very small alignment tolerances.

Single mode waveguides, but planar light wave circuit (PLC), are also used in module and chip-level applications (computer communication) for interconnects over shortest distances. The integration of waveguides in silicon (Silicon Photonics) is of great importance here. In this area, there are already approaches for optical bus coupling via ring resonators [18, 21].

These areas—and thus single mode waveguides in general—are irrelevant for the device communication, as they deal with either extremely long (> 1 km) or extremely short (< 10 cm) transmission distances. For this reason, they will not be discussed in detail in this book.

The relevant range for the device communication and thus for this work can be limited to connection lengths of 0.1 m to 100 m. Multimode waveguides with larger core cross sections are suitable for this purpose. The advantages are less critical tolerance requirements, which simplifies production and assembly significantly. The disadvantages of multimode transmission (higher attenuation and mode dispersion), on the other hand, are not relevant for such short transmission distances.

Because multimode fibers have their first optical window at $\lambda = 850$ nm and the often used GaAs-based vertical-cavity surface-emitting lasers (VCSEL) have a great availability at this wavelength, 850 nm is established as the standard wavelength in optical short-range connections. Hence, the approaches presented in this book are based on this wavelength as well.

To achieve waveguide networks in and on structural elements, there are already solutions to embed fibers into carbon fiber-reinforced polymers (CFRP) [22, 23]. However, this is a very complex process. Furthermore, it cannot be used with other materials and the coupling to and from the fibers is very difficult. Hence, this technology is more suitable for structural health monitoring with fiber Bragg gratings than for the communication between several devices.

More suitable for the connection of different modules or devices are optical networks in printed circuit boards. These so-called electro-optical printed circuit boards (EOPCB) use embedded glass layers for the optical routing and out-of-the-plane coupling elements to connect different devices [16, 24]. The major disadvantage is the limitation to 2D. Although there are solutions for stacked EOPCBs, where a 3D light path between different layers is possible, there is still no possibility to realize bends or curves in the vertical direction [25, 26]. Furthermore, these technologies are limited to the PCB-environment with a high effort for the fabrication of the glass panel-based waveguides, which is not flexible enough for the device communication.

To increase the potential of optical short-range connections for the device communication, arbitrary waveguide networks on three-dimensional surfaces are needed. According to that, there is a demand for new manufacturing techniques for multimode waveguides.

1.2.2 Optical bus systems

Even though there is already research successes in the field of optical computers [27], the processing and storage of information are currently exclusively electrical. For this reason, optical transmission always requires electro-optical (e/o) and opto-electrical (o/e) conversion. Discrete semiconductor lasers (edge or surface emitters [28, 29]) are usually used for e/o conversion, but integrated lasers for silicon photonics are also available [30]. Either they are directly modulated or a separate modulator is added. The conversion of the received signals is usually done by photodiodes [32] and the corresponding processing circuit [10].

There are two theoretical options to connect more than one e/o module: parallel point-to-point interconnects or bus coupling. The first possibility is the connection of the modules/participants (e.g., sensors) to the base/control side (e.g., central processing unit) with several waveguides, i.e., every interconnection has its own transmission path. This has the advantage that, in the event of failure of a waveguide, only one module is affected. However, the following disadvantages are associated with that:

- Very complex hardware on the base side
- Design of a huge cable harness with numerous single waveguides
- High space requirements.

Due to the described limitations when using several e/o modules, the disadvantages outweigh the advantages of optical communication compared to the electrical pendants. Hence, optical transmission has not been established for device communication applications yet. A solution to this challenge would be the second possibility of transmitting a signal: via a bus system. According to the definition, a bus is a shared transmission path between several nodes, in which two nodes communicate while the rest remain silent [32].

For optical transmissions, a ring bus—as shown in Fig. 1.4—is preferred, since the direction of propagation of the light does not have to be changed. Hence, additional splitters/combiners for splitting into transmitting (Tx) and receiving (Rx) elements or light deflecting elements (mirrors, fiber Bragg gratings) are not required. An additional advantage of such an optical bus system is the possibility of using wavelength division multiplexing (WDM) [32] either to enable simultaneous communication between several nodes or to integrate several logical buses with different wavelengths into one physical bus. The disadvantage is that

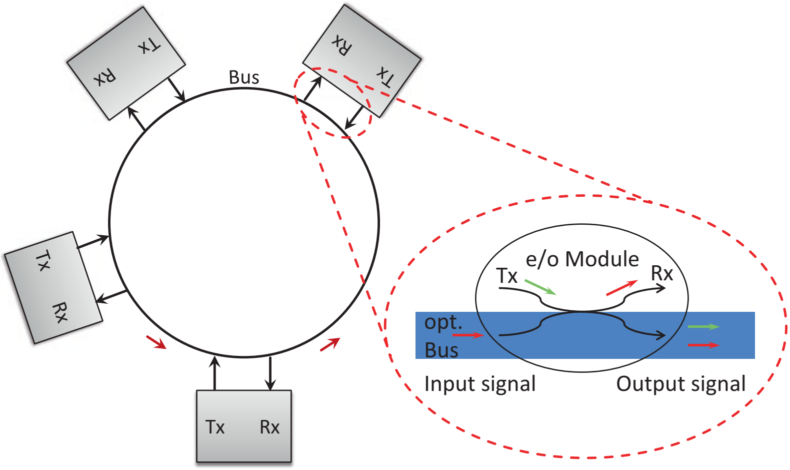


Fig. 1.4 Schematic of an optical ring bus and the required optical bus coupling [10]

all nodes in the system share the power budget of a single bus. All advantages and disadvantages of the optical ring bus are summarized in Table 1.3.

The fact that all modules share the power budget of one bus has led to the fact that no practical concept for optical bus coupling could yet be developed, as it will be discussed in Chap. 6. Hence, the possibilities for the transmission from one waveguide to another are still limited to butt coupling or grating couplers, which both need an interruption of the two coupling partners. On the other hand, parallel (bus)connections are standard in the electric domain.

1.2.3 Current development in the field of 3D-Opto-MID

As mentioned earlier, the integration of optical paths and elements into 3D-MID is getting more and more important. One example is the asymmetric optical bus coupler (AOBC) which will be described in Chap. 6. For that, a defined radius of one of the coupling waveguides is crucial, which is why a 3D assembly is necessary.

Table 1.3 Overview of the advantages and disadvantages of an optical ring bus

Advantages	Disadvantages
Simple cable harness (in ideal circumstances only one waveguide)	All modules share the power budget of the bus waveguide
Flexible reconfiguration of the network	The bus waveguide needs to be connected to its origin
In theory an arbitrary number of modules can be connected	
No loss of power if a module is disconnected	
Parallel use of the bus waveguide with WDM	

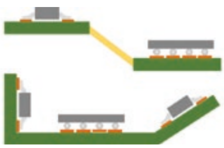
The former definition of 3D-MID is three-dimensional molded interconnect device. A newer and more accurate definition is 3D mechatronic integrated device, since the carriers are not necessarily fabricated by injection molding [33]. There are other techniques, e.g., 3D printing of polymers/ceramics or laser sintering of ceramic materials [34, 35], which allow for fabrication of 3D assemblies.

To understand what 3D means in this context, a geometrical classification of electronic assemblies is necessary, as summarized in Table 1.4. The first group consists of conventional two-dimensional circuit carriers. This includes printed circuit boards (PCB) as well as thick-film ceramics, which are fabricated on one planar surface. If there are multiple flat surfaces, which are not in the same plane, the assembly is classified as 2.5D. This could be a rigid-flex PCB or stacked rigid PCBs to allow elements in the vertical direction [36]. Freeform surfaces in 3D, on the other hand, are only achievable with 3D-MID and—only to a limited extend—with flexible electronics [33, 37].

The potential of three-dimensional assemblies, especially of 3D-MID, lies in the high geometric design freedom. According to that, it is possible to adapt the electronic parts to the geometry (coolers, alignment or functional structures, etc.), which allows for high flexibility and higher degrees of miniaturization due to higher package densities. Furthermore, for some applications it is crucial to obtain defined angles and/or radii between single parts, which is only possible with 3D-MID. [33]

However, because of a more difficult manufacturing compared to planar fabrication and assembly processes, 3D-MID stays behind standard techniques in terms of throughput. Furthermore, holistic design tools for mechanical, thermal, electrical and optical properties are not available for 3D-MID, which complicate the design process compared to standard PCB or ceramic assemblies. In addition, thermal management has to be considered when choosing the substrate material,

Table 1.4 Classification of packages according their spatial dimensions (adapted [33])

2D	**2.5D**	**3D**
Planar process surface	Multiple plane surfaces	Freeform surfaces
		
Standard PCBs, thick-film ceramics,	Rigid-flex PCBs, Stacked PCBs	3D-MID, flexible PCBs
+ High throughput + Matured technologies and design tools + Suitable for temperature critical applications - No functionality in vertical direction	+ High throughput + Flexion/Twisting possible + Functionality in vertical direction - Manual assembly of the single parts	+ Function integration + Three-dimensional design freedom + High degree of miniaturization - Difficult part assembly - No holistic design tools

which then influences the choice between PCB, thick film, flex PCB and 3D-MID. Hence, it always has to be carefully considered which requirements are made on the assembly and which production technology is then suitable and adequate for it.

To increase the potential of 3D-MID, [33] made several proposals:

- In order to address high current applications, thermally conductive materials are necessary.
- For optical applications, which need stable temperatures for LEDs and lasers, heat dissipation concepts have to be made.
- Improved 3D placement and interconnection as well as embedding technologies allow for higher throughputs and higher package densities (chip on MID).
- Holistic design tools are necessary to improve the R&D steps prior the fabrication.

1.3 New Approach for Additive Manufactured 3D-Opto-MID

For the upcoming applications in the device communication, the advantages of optical transmission were pointed out. However, in contrast to optical links on PCB or rack level, there is a lack of short-range connections on three-dimensional structural elements. This leads to the demands described in the previous subchapters. The goal of the presented work is to increase the competitiveness of optical short-range connections for the device communication compared to electrical pendants. Four main challenges could be identified:

- There is a demand for new waveguide manufacturing techniques for 3D.
- New coupling schemes are required to achieve optical bus systems.
- Classical 3D-MID needs to be extended by an optical functionality toward 3D-Opto-MID.
- For the development of such systems, a holistic design/simulation tool is necessary.

In this book, we want to address all of these issues in an interdisciplinary research. The question we want to answer is:

How is it possible to increase the competitiveness of optical short-range connections for the device communication on 3D structures in terms of waveguide design, simulation, fabrication, coupling and packaging?

This question is successively solved in an interdisciplinary research attempt (Fig. 1.5) throughout the single chapters of this book, beginning with the modeling and simulation followed by the conditioning of the substrate and manufacturing of the waveguides. At the end, a 3D-Opto-MID package for optical bus coupling is presented and the impact of the novel technology is evaluated.

To understand the decisions, made in the single chapters, a preview of the solution is necessary. To achieve maximum flexibility for arbitrary waveguide networks

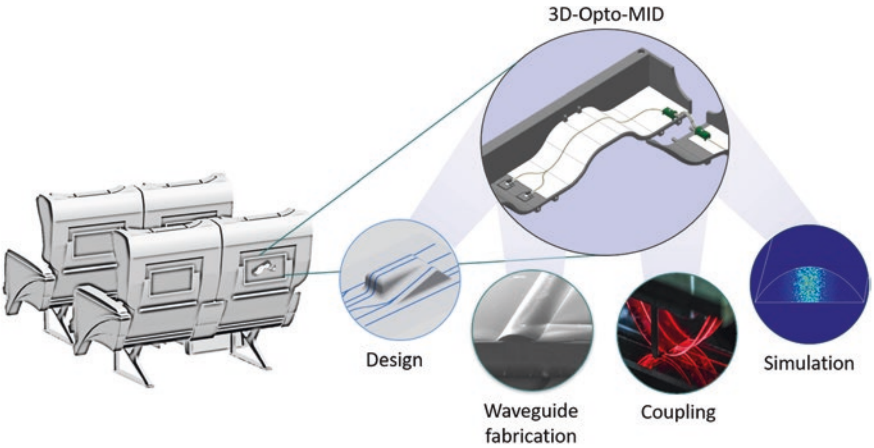


Fig. 1.5 Illustration of the interdisciplinary research topic of additively manufactured optical waveguides for 3D-Opto-MID by the example of a module for infotainment systems

on 3D surfaces, the core of the presented research approach is the additive manufacturing of multimodal waveguides using aerosol jet printing. It has a high potential for three-dimensional applications. The possibility to print waveguides on 3D surfaces brings optical short-range connections to a new level. Chapter 5 contains the detailed discussion of aerosol jet printing compared to the state of the art.

The main challenges of printed polymer waveguides are their unique cross section (circular segment) and the waviness along the waveguide. To control the latter one and to increase the possible aspect ratio of the core, conditioning lines are used, which influence the wetting behavior of the substrate related to the core material. This leads to an increased height of the circular segment at the same width. The application of these conditioning lines is discussed in Chap. 4. The whole approach is depicted in Fig. 1.6.

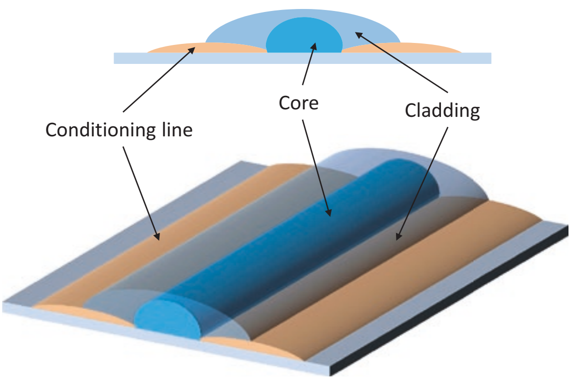


Fig. 1.6 Schematic of an aerosol jet printed waveguide with conditioning lines to increase the aspect ratio of the core

The coupling of these waveguides is another challenging task, which is described in detail in Chap. 6. The asymmetric optical bus coupling (AOBC), developed in this work, allows for interruption-free, bidirectional waveguide coupling, especially for photonic bus systems. Crucial for this coupling method is the bending of one of the coupling partners out of the plane (in vertical direction), which is why 3D substrates are necessary. Hence, classical 3D-MID is extended to include optical functions.

Furthermore, an all-new design tool is developed in Chap. 2, which allows for optical *and* electrical routing on 3D substrates including a standardized parameter pass to an optical simulation tool. It extends mechatronic data models by adding optical properties and functions. This creates a design that is adapted to the individual manufacturing processes. The simulation is especially developed for multimode waveguides with arbitrary cross sections and will be presented in Chap. 3.

Overall, the complete process flow for additively manufactured waveguides for 3D-Opto-MID is portrayed from the design, simulation toward the manufacturing to the final package and assembly.

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2 Computer-Aided Design of Electro-Optical Assemblies

Jochen Zeitler and Jörg Franke

Abstract

The integration of the different engineering disciplines in an integrated development procedure is the core of this chapter. For this purpose, the physical and technological principles of optical technologies must be considered. Product development methods of technical systems are a related field, since up to now, especially for 3D-Opto-MID, no adequate methodology exists. Analogies to mechatronic systems and their sub-processes do exist, but these must be evaluated and expanded with regard to the new optomechatronic components. A separate procedure that differs from conventional development methods is just as important as the challenges that must be placed on modeling systems, the designer and the production of the 3D-Opto-MID. From these defined requirements, it was possible to derive a concept for a 3D optomechatronics CAD software (OMCAD) which contains the essential steps for creating these products.

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This chapter focusses on the methods and development of a software-based methodology for designing 3D-Opto-MID. The aim is to show a general concept for designing these cross-domain assemblies.

2.1 Demand on Software-Based Design Tools for Spatial Optoelectronics

The integration of electrical functions into mechanical components has been intensively researched over the last 20 years. In view of the potential offered by the integration of optics into electrical and mechatronic components, the research of a new class of interdisciplinary products is therefore obvious. Until now, optical interconnects have mostly been based on optical fibers or planar electro-optical circuit boards. Current research is focused on the complete integration of optical functions into three-dimensional and spatially complex components. These components are a combination of well-known MID technology (see Fig. 2.1) and the application of optical structures, so-called 3D-Opto-MID. To be able to manufacture these products, new processes and technologies are needed for stable and efficient production.

According to the production technology aspects, the planning process for stable systems and applications is also crucial. The use of computer methods to solve scientific and technical problems has already proven to be extremely effective in areas such as mechanical, electrical and mechatronic development.

In the planning process of new products and production plants, this class of computer-aided tools is referred to as engineering software. The same software is based on mathematical models containing both analytical and numerical methods. The goal of this engineering software is to capture one or more aspects of a real or planned system. Although modern computers have enormous computing power, they still rely on robust algorithms to keep the processing time low and reduce the number of faulty solutions. Knowledge-based engineering software increases user productivity, especially in the design process, by transforming data into explicit knowledge. This can be done in different ways: For example, geometric, electrical and optical data from manufacturing can be collected and used to define design

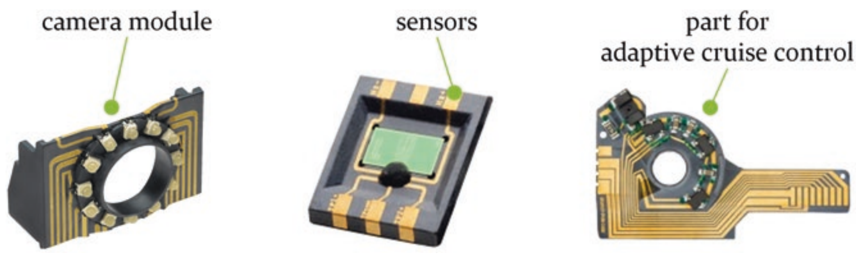

Fig. 2.1 Exemplary representation of a 3D-Opto-MID including its components [1]

rules. These help the product developers by uncovering undesirable developments in general. The more complex the system, the more difficult it is to realize such implicit arguments. On the other hand, in some cases, short notifications in the user interface with hints on problems are helpful to get attention to errors at an early stage [2]. An example can be found in the design of mechanical components and electronic circuits. These rely on a large portfolio of established computer-aided design (CAD) and electronic design automation (EDA) software tools. For example, printed circuit boards and production processes can be simulated extensively, or a wide variety of configurations of component placements can be tested to exploit the available space. In contrast, only a small number of software solutions are available for the relatively young technology of MIDs, which describes this integration of mechanics and electrics. The engineering discipline of optics, which is coming to the fore, further expands these challenges.

From this, the future need for tools can be derived that allow the production- and function-oriented design of spatial optomechatronic structures. These must combine functions from mechanical CAD (MCAD), electrical CAD (ECAD) and optical CAD (OCAD). Since there are no solutions available in this field so far, a fundamental research of these novel systems is necessary.

Against this background, the work of the research group OPTAVER is intended to contribute to the development of integrated optomechatronic assemblies. The goal is to realize optical conditions in interaction with the discipline of mechatronics in a holistic product development process for the development of optomechatronic assemblies (see also Fig. 2.2).

To this end, approaches to the design of such products must be demonstrated and evaluated using a computer-aided modeling system. The latter requires, as in a conventional CAD system, an appropriate graphic development environment, functional structures for the integration of electrical circuits as well as

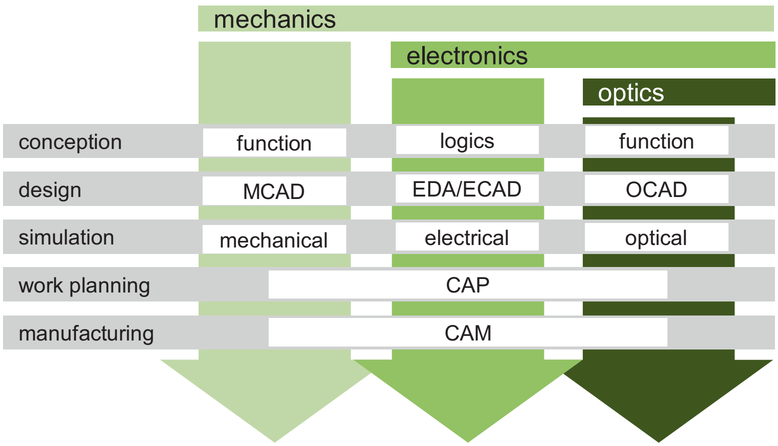

Fig. 2.2 General design process of electrical, optical and electro-optical circuits

functionalities for the design of optical networks. Therefore, it is necessary to identify relevant partial aspects and components to be realized in such a system. Based on these results, a procedure for optomechatronic product development will be derived. Physical and production-related influences play just as much a role here as the given conditions.

2.2 State of the Art in the Design of Electro-optical Circuits and MID

In the next subsections, development procedures for domain-specific and cross-domain systems will be explained. The focus here is primarily on electrical, MID and electro-optical assemblies.

2.2.1 General Procedures for Electronic and Electro-optical Assemblies

The basic purpose of a process chain for electronic and electro-optical product development is to transfer a functional idea into a working chip or circuit board using a reproducible process (the process chain). The result should be a functional system. Even if the design of simple photonic components can be done intuitively, a reproducible process supported by efficient software tools is of crucial importance. [3]

For both electronic and optical systems, the first step is to formulate basic concepts or ideas at a high level of abstraction. Afterward logical relations of different function modules can be captured in subsequent steps. In the literature, this first step is generally referred to as front-end design or schematic capture. [3]; [4]

Analogous to this, there is the back-end design or layouting, which essentially includes the design of the circuit carriers, the placement and routing of components as well as functional and design rule checks. In the case of electronic circuit boards, these can include the distances between the tracks and other important components or basic geometric dimensions (e.g., width of the track, size and spacing of vias, distances to the board contour). Finally, the post-processing takes place. In detail, the steps are structured as follows [3]:

- *Design capture:* The function idea is converted to a schematic plan consisting of logical blocks or hierarchical subsystems. There may be an investigation of different circuit architectures or topologies with different selection of devices.
- *Circuit simulation:* The logical circuit is simulated, and its parameters are optimized to make it work as intended.
- *Circuit layout:* The logic circuit is converted into a mask layout representation that can be used for manufacturing.

- *Verification:* The layout is checked for errors to ensure that it is compatible with the manufacturing process, and simulations are performed to ensure that the layout performs the desired function.
- *Manufacturing:* The generated layout data goes through a series of post-processing steps to convert it into the actual formats. The assembly is then produced on the basis of this data.
- *Testing:* The manufactured product is tested, and the results are compared to the original design. If necessary, design information is updated to improve the next generation of designs.

For better understanding, the next three sections will focus on the specific design processes for electronics, 3D-MID and electro-optics.

2.2.2 Electronics Design Process

Very large-scale integration (VLSI) describes the process of embedding a geometric chip layout from an abstract circuit description. This can be, for example, a netlist that is transferred to a physical layer such as silicon [5]; [6]. The final product is an integrated circuit (IC). At a higher level in the design process and on a smaller scale, the purpose of printed circuit board (PCB) design is to create a geometric layout by mounting VLSI components (e.g., chips) and laying traces on a printed circuit board. In the early years of semiconductor technology, designs were created manually on paper. Soon, however, with the increase in the number of transistors on a chip and improved semiconductor manufacturing processes, new automated tools became necessary to facilitate the design process—electronic design automation (EDA) systems. These tools are mainly used to generate new chips and circuits [5]. In VLSI and PCB design, there are fundamental elements that need to be optimized simultaneously: area, speed, power dissipation, design time and testability. Partitioning on different levels is a typical example that illustrates the decomposition of a system into small subsystems down to the smallest logical blocks. [6]

According to Gajski and Kuhn [7], there are three design areas, each with its own hierarchy:

- The first area is the behavioral domain, where design is described on a functional level by mathematical equations or Boolean algebra.
- The second area is the structural domain, which defines a circuit as the composition of subcircuits (e.g., transistors that form a NAND gate at the chip level or electronic components that perform a specific function at the PCB level).
- The third domain, the physical domain, provides information about the location of the circuit elements.

Figure 2.3 shows the process of designing electronic circuits on different levels for IC, multi-chip module (MCM) and PCB.

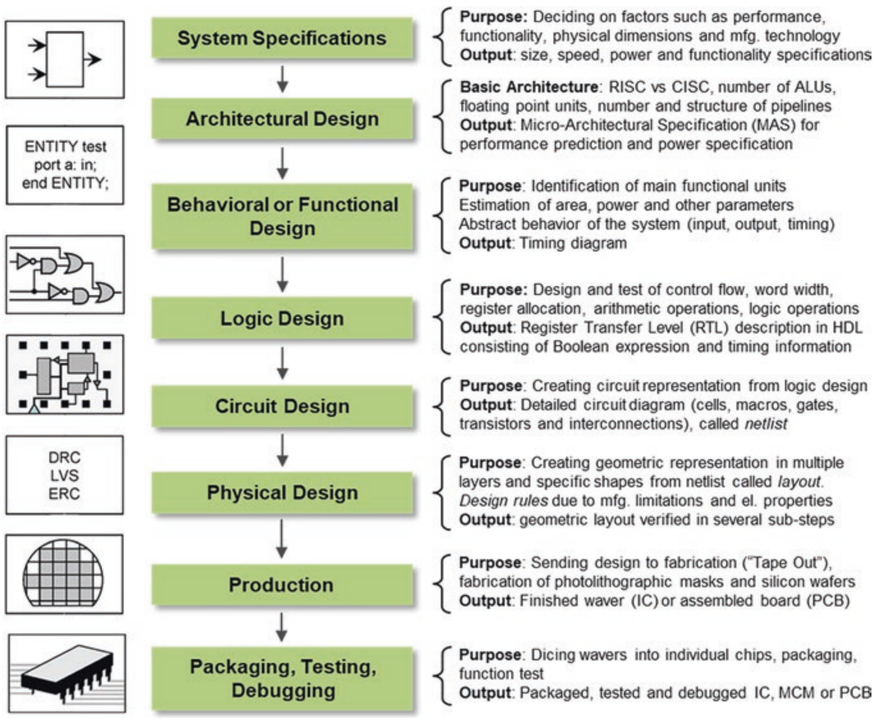

Fig. 2.3 Important steps of the digital design process with its purpose and output (based on [8])

The correctness of the created layouts can be checked by different verification methods. A practical approach is prototyping, where a working design is assembled from discrete components on breadboards. However, this becomes very complex with a large number of components. Simulation tools based on computer models analyze the output signal for a given input signal. As the layout with its internal states and possible input signals grows, simulation also reaches its limits.

2.2.3 Procedure for Spatial Electronic Assemblies (3D-MID)

3D-MID is a further development in contrast to the classic planar formwork carrier. MIDs are complex mechatronic systems, which not only focus on the electronic layout, but also require close cooperation between the mechanical and electronic development departments through function integration. However, many companies still do not use MID-specific systems for the development of new products. There are already guidelines in place, all of which pursue the goal of reducing the high complexity of development by means of a process model. In addition to the procedure according to PAHL/BEITZ [9], the guideline VDI 2206 [10] is