CONSTRUCTION KIT FOR MICROOPTICAL SYSTEMS ON THE BASIS OF MICROOPTICAL BENCHES

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ABSTRACT

Manufacturing test structures of microsensors and microactuators is very expensive in terms of time and materials. In a conventional design process, this limits the number of design variants to be considered. For this reason, computer-supported design techniques are gaining importance in microsystems technologies. In contrast to microelectronics which may be considered two-dimensional in first approximation, a number of microoptical systems extend over three dimensions. As a consequence, a monolithic setup of such systems is not possible, as this would give rise to topological and geometric problems. Another reason for the modular concept of complex microoptical systems is the lacking of a uniform material system (in contrast to microelectronics). The modular setup of these hybrid systems results in an isolated manufacture of the individual components and their later assembly in a single system. An important aspect of construction is to ensure a certain functionality of the combined system, which is closely linked with the geometry of the structure and the application conditions. To maintain the overall function of a microsystem under the given manufacturing conditions and application environments to be expected, the system design has to be checked for interactions and adjusted accordingly. Hence, simulation of microsystems as a function of performance-reducing impacts plays a crucial role.

The concept presented in this paper is the computer-aided design of a modular system on the basis of a microoptical construction kit of reusable models of fundamental microoptical elements.

1. INTRODUCTION

When developing mechanical systems, the entire process from the specification of the component to the preparation of drawings can be handled by the designer. Tools for simulating mechanical stress are integrated in the CAD environment used and, thus, enable the designer to immediately check the construction for complicated and highly stressed components. Development of hybrid microoptical systems that are fabricated with a specific fabrication technique is different. In this case, the above-described structure is missing. The main feature of hybrid setups is the combination of different materials and components. In many cases, knowledge on the processes and the material is not available to the required degree. Frequently, the development of a new microoptical system becomes a research project with all the risks in terms of time and money. Different domains like e.g. optics, mechanics, fabrication techniques, and assembly are separated to a great extent as are ambient influences while operating the final product. In microoptical design, the requirements in terms of assembly (e.g. needed space) or deformation of the material due to ambient stress usually are not known or considered. Structures of the microsystem without optical functions (e.g. mounting structures, alignment structures, helping structures for assembly, etc.) will not be considered in the optical design, as the optical simulation tools do not offer the functionality for the consideration of these structures. Nevertheless, these structures can influence the optical performance (e.g. under changing ambient conditions, alignment structures may deform and misalign the optical component) or the optical design (e.g. if the optical design is too compact and no space for feeding is left, an actually unneeded redesign has to be carried out). In the next step of the usual design process, the finished optical design has to be translated in a mechanical description, where the requirements of the fabrication processes will be considered. At the end of the process chain, the individual components will be assembled and the microsystem will be finished as regards the specifications. Due to the absence of adequate interfaces, information transport from design level to design level is very difficult. If changes influencing the optical property of the design have to be made in the following process steps, the whole process chain, beginning with the optical design, has to be repeated. This is associated with a huge amount of costs and effort. To allow for an efficient use of technology tools and to achieve a fast cycle from the system's design via the system's prototype to series production, we propose the concept of a library of microoptical fundamental elements. These fundamental elements (or microoptical primitives) consist of simple holding or alignment structures assembled with a passive or active optical component, respectively.
Models of these microoptical primitives have to be defined as reusable software units. In addition to the production knowledge the requirements resulting from the handling and assembly of the real microoptical component must be included in the individual models (design for assembly). A CAD model of the primitives has to be stored in the model library as an interface between functional modeling and fabrication. Each primitive stored in the microoptical construction kit is described by its CAD model, its optical model, and its process parameters. On the basis of these models, a software library, the microoptical model construction kit, can be built up (Figure 1). Adding the primitive models with well-defined I/O characteristics will result in a model of a complex microoptical system.

2. CREATIONS OF THE MODELS AND SETUP OF THE SUBSYSTEM

Generation of models describing the primitives in different ways must follow discrete steps. The first step is the identification of those structures of the microoptical system, which are worth storing in a model library in the sense of reusability. This is a main point, since the emphasis of the approach lies on the reusability of the models for the primitive’s model to be used in the setup of different optical applications. Once the fundamental elements are identified, they have to be individualized. In this step, all interactions between neighboring structures, which are not negligible, have to be considered. The individualization of the primitives also has to be carried out on the CAD level, i.e. the identified primitive has to be individualized in a CAD system as well.

The CAD model serves as input for FEM analysis to simulate the behavior of the structure under realistic conditions (e.g. temperature variations due to changes in the environmental temperature (day-night fluctuations or seasonal fluctuations), or pressure loads, etc.). In a next step, structural changes due to the environmental effects, e.g. geometrical changes of alignment structures of optical components, have to be detected and analyzed. If the structural changes influence the optical properties of the optical function element, this influence has to be determined and included in the optical model. Here, different types of considerations are possible: The geometric data can be used for a tolerance analysis or included as a static positioning shift or tilt of the optical element.

If the impact on the optical functionality caused by the ambient conditions is too large, a direct redesign has to be carried out on the FEM level to minimize this effect. This redesign is evaluated by the optical simulator and if the impact on the optical performance is satisfactory, the structural changes made in the FEM tool are transferred to the CAD model. Both, the CAD model and the optical model are stored in the microoptical model library together with the process knowledge (see Figure 2). Of course, the process knowledge as well as requirements resulting from the handling and assembly of the real parts have to be considered while creating the CAD model.
Standard have to be defined subject to which the primitives have to be optimized. These standards are describing a “standard environment” within all the primitives are fully characterized.

Since the models of the primitives have been characterized optically and have a well-defined I/O behavior, they can be used to build up models of complex optical systems or subsystems (see Figure 3). Figure 3 also shows on which level which fabrication technology is employed.

3. THE HETERODYNE RECEIVER

The concept of the construction kit will be illustrated using the modular set-up of the LIGA heterodyne receiver as an example. The heterodyne receiver is a coherent optical receiver module. The basic idea underlying coherent light wave systems is to overlap the received signal coherently with another optical wave that is generated locally at the receiver by a semiconductor laser diode. The thus generated heterodyne signal is detected by the photodiode and amplified as a function of the signal intensity of the local oscillator.

In practice, the design of a balanced polarization-diversity heterodyne receiver in connection with laser diodes of small line width is preferred for coherent optical systems [1]. This receiver module is presented in Figure 4.

### 3.1 Identification of the Primitive Structures

An important step in the shown modeling approach is the identification of the fundamental structures. As described in section 1, such a fundamental structure has one optical and one mechanical function at the maximum. The modular setup of the heterodyne receiver facilitates the identification of these structures (Figure 5):

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1 The “standard environment” is specified by a defined temperature range, defined tension/stress/pressure, etc.
- The primitive fiber: composed of the fiber mount and the fiber
- The primitive ball lens: composed of the ball lens and its alignment structure
- The primitive photodiode: composed of the photodiode and its alignment structure
- The primitive prism: composed of the four prisms and the alignment structures

The different optical functionalities of the components (active or passive, focusing or beam-splitting) are coupled with the mechanical function (positioning/adjustment or simply holding) of the optical bench.

4. PERFORMANCE-REDUCING IMPACTS

Performance-reducing impacts are mainly found in the fields of manufacturing, ambient temperature, and physical/optical phenomena. The holding structures of the heterodyne receiver are manufactured by means of the LIGA technique.

An important feature which affects the functionality of the receiver module results from the place of its use. Influences of daily or seasonal temperature fluctuations on the receiver structure have to be simulated. These simulations are carried out by means of the finite element method. If material distortion is known as a function of ambient temperature, the resulting changes of position of the optical components may be taken into consideration in optical simulations.

4.1. Simulation of the Effect of a Temperature Load Using the Primitives Fiber and Ball Lens as Examples

Due to the modular, pre-adjusted set-up of the LIGA heterodyne receiver, the holding structures are of crucial importance, as they are responsible for the exact positioning of the optical components in the beam path.

In this section, the effect of a temperature change on the structure and shape of the holding systems of the fiber and the ball lens shall be investigated. The temperature change used for this investigation amounts to 40°C, the reference temperature is 20°C.

The structure of the holding elements after application of a temperature load of 40°C is shown in Figure 6. The coordinate system is selected such that the z-axis indicates the direction of beam propagation. Bulging of the fiber holding element structure is clearly. It causes a displacement of the fiber shaft and, hence, a displacement of the fiber position. The displacement values for the spatial coordinates are presented in Table 1 for the primitive fiber.

<table>
<thead>
<tr>
<th></th>
<th>x-displacement</th>
<th>y-displacement</th>
<th>z-displacement</th>
<th>inclination</th>
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<td>2.56µm</td>
<td>1.51µm</td>
<td>0.037°</td>
</tr>
</tbody>
</table>

Table 1: Effects of a temperature load of 40°C on the holding structure of the fiber.

In case of the primitive ball lens, a temperature load in the given temperature range has no effect on the lens position, since the dilatation of the holding structure is isotropic and the holding structure is not able to deform the ball lens. This is due to the much higher Young’s modulus of the lens material (BK7) compared to the structure (PMMA). The positioning structure of the ball lens therefore is non-critical in the given temperature range, as a result of which the primitive ball lens can be stored in the microoptical construction kit as a reusable microoptical fundamental structure defined and characterized in the given temperature range.

Depending on their effect, two groups of position tolerances of the optical components may be distinguished in the case of the primitive fiber:

![Figure 6](image-url)
• Axial position errors: Position displacements along the z-axis lead to a change of the characteristic beam parameters, if the distance $l_1$ is affected, and to a change of the beam profile at the point of the photodiode, if the distances $l_2$, $l_3$, and $l_4$ are affected. These position uncertainties result in a mis-agreement of the overlapping wave fields at the photodiode. This may be “measured” via the coupling efficiency.

• Lateral position errors: Position errors in lateral direction to the optical axis or tiltings of the optical components cause a displacement of the irradiance distribution. This deflection of the irradiance distribution leads to a direct loss in the heterodyne signal, as the overlap between the received signal and the local signal is reduced.

5. MODEL OF THE MICRO OPTICAL SUBSYSTEM OF THE HETERODYNE RECEIVER

Since every primitive is characterized subject to its operational environment, the system's performance can be simulated in a realistic way. Effects of axial and lateral displacements of the fiber due to a deformation of the fiber’s positioning structure resulting from a temperature load of 40°C on the heterodyning of the signals shall be dealt with in the following sections. The effects of the position errors calculated by means of the FEM models on the system’s performance can be determined with the aid of the optical model. Furthermore, the limit value of the tolerance range acceptable for the individual application can be determined.

5.1. Effects of Axial Position Errors

To determine the effects of axial misalignment of the primitive fiber on the coupling efficiency, the overlap integral between the signal disturbed by misalignment and the undisturbed signal is formed.

![Figure 7: Coupling efficiency as a function of the change of distances between the fiber and the ball lens due to fiber displacement.](image)

Mutual axial misalignment of the primitives results in a change of the distances. The influence of this effect on the wave field is illustrated in Figure 7 by the change of coupling efficiency as a function of the change of the distances $l_1$.

The tolerance range is shaded gray. Over the entire variation range, no effects on the coupling efficiency between the disturbed and the undisturbed wave field are observed. This is due to the collimation of fiber radiation. Consequently, the wave field is hardly changed within the relatively small variation ranges of the distances. Functioning of the heterodyne receiver is not adversely affected by axial effects of the primitive fiber.

5.2. Effects of Lateral Position Errors

The performance-reducing mechanisms discussed in section 5 do not only cause an axial misalignment of the primitives as described above, but also a lateral displacement and a tilting. Lateral misalignment results in the displacement of the center of gravity of the irradiance distribution of the disturbed beam path. This reduces the overlap between the local signal and the received signal. In the following section, the position of the center of gravity of the irradiance distribution and the coupling efficiency between the beam paths to be overlapped are studied as a function of lateral misalignment of the primitives. As an example, the effects of a dislocation shall be illustrated for the primitive fiber. For this, it is proceeded as follows: The wave field propagates through the disturbed optical system. The resultant irradiance distribution at the photodiode is calculated. From this distribution, the coordinates of the center of gravity are determined in accordance with the ISO regulation [3]. Then, the displacement of the center of gravity is represented graphically as a function of misalignment. Figure 8 shows the effects of lateral misalignment of the fiber. The left column gives the irradiance distribution for a maximum fiber dislocation within the limits of tolerance. The sectional view below indicates the Gaussian distribution. The center column shows the displacement of the center of gravity as a function of fiber displacement. Coupling efficiency is represented in the right column as a function of lateral misalignment of the fiber. The tolerance range is shaded gray. A maximum lateral displacement of the fiber by $\Delta_y=-3.3\mu m$ is found to result in a displacement of the center of gravity by $21\mu m$. This displacement nearly corresponds to a quarter of the beam diameter at this point. Coupling efficiency is reduced by 55% to 0.45 due to the maximum displacement of the fiber within the limits of tolerance.

5.3. Discussion of the Results

In sections (5.1, 5.2), ambient effects (i.e. temperature variations) on the optical performance were illustrated.
using the primitive fiber as an example. Change of the ambient temperature resulted in two different effects:

- axial position error
- lateral position error

Knowing this result of optical modeling, the optical designer can directly react. There are different possibilities of reacting. One of them is to create compensating structures in the optical model to weaken the effect on the optical performance. Another possible reaction is to redesign the mechanical structure of the positioning element in order to attenuate its sensitivity to temperature changes.

To be stored in the microoptical construction kit, the primitive fiber has to undergo a redesign: The FEM model has to be corrected so as to minimize the structural change caused by the temperature. This has to be evaluated in the simulation of the optical model before the structural change is carried out in the CAD model.

### 6. CONCLUSIONS

In this article, an approach to generating a model library of reusable, parameterizable, typical basic optical components was outlined. These fundamental elements (or microoptical primitives) consist of simple holding or alignment structures assembled with a passive or active optical component, respectively.

Models of these microoptical primitives have to be defined as reusable software units. In addition to the production knowledge, the requirements resulting from the handling and assembly of the real microoptical component must be included in the individual models. On basis of these models, a software library, the microoptical model construction kit, can be built up. Adding the primitive models with well-defined I/O characteristics will result in a model of a complex microoptical system. Each primitive stored in the microoptical construction kit is described by its CAD model, its optical model, and its process parameters. A point of high importance is the bringing together of fabrication aspects (represented by the CAD models) and functional aspects (represented by the optical model) during modeling already. This strategy enables the system designer to consider both the requirements arising from the production process as well as effects of other physical domains, e.g. ambient influences.

The concept of the microoptical construction kit was illustrated using the application of a microoptical heterodyne receiver as an example. Here, the identification of fundamental structures, the so-called primitives, was shown. The effects of ambient influences on the optical performance of the system were illustrated by a temperature load of 40°C on two exemplarily chosen primitives. It was demonstrated that the design of the alignment structure of the ball lens was very robust to temperature changes, while the design of the fiber mount must be changed to comply with the defined requirements. Further work has to be done to complete the microoptical primitive library. Therefore, more microoptical systems have to be investigated and individualized. The investigation has to be carried out under the aspect of reusability of the fundamental microoptical element in different applications.

### 7. REFERENCES

