Tolerance Compensation in Micro-Optics

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ABSTRACT

In contrast to microelectronics which may be considered two-dimensional in first approximation, micro-optical systems extend over three dimensions. Due to the lack of a uniform material system, complex micro-optical systems are constructed using a modular concept. The modular setup of such hybrid systems results in an isolated manufacture of the individual components and their later assembly in a single system.

Designing a micro-optical system, all relevant requirements and constraints defined by the manufacturing processes and the application of the system in a real ambience must be considered. Furthermore, every individual manufacturing step adds its own tolerances to the system. To maintain the overall function of a system under the given manufacturing conditions, the system design has to be robust with respect to the expected tolerances. The system's robustness will result from considering process knowledge in the state of modeling already. Process knowledge of non-silicate manufacturing processes is collected and stored in a knowledge database. On basis of these data, process-dependent inaccuracies and tolerances can be used to design robust functional components and functional units (subsystems). This approach of robust, tolerance compensating design is applied to the design of an infrared gas sensor, a micro-optical distance sensor, and a lens of variable refraction power.

Keywords: Micro-optics, tolerancing, modeling, simulation

1. INTRODUCTION

When transferring micro-systems technology to products, target-oriented application of computer-based design- and simulation- tools is of fundamental importance. With the help of design tools, the time needed for the development of micro-systems can be shortened and the reliability of the systems in operation can be increased.

In this context, robust design is of high relevance. Briefly, robust design must fulfill the following three requirements:

- Adjustment to the process chain/design rules (design for manufacturing)
- Compensation of tolerances
- Analysis of and compensation for ambient and operational effects

This paper will focus on the application of the robust design strategy to the design of three devices, an infrared gas sensor, a micro-optical distance sensor, and a lens of variable refraction power.

2. APPROACH

Fabrication of systems is subject to tolerances. In manufacturing, every individual process step has its own accuracy, thus causing tolerances of components or of the subsystem as a whole. In case of micro-optical systems, the accuracy of the fabrication chain often is crucial. Frequently, modifying the design of the individual components can reduce the influences of tolerances on the system's performance. If tolerances are not known and, hence, the system's design cannot be adjusted to this demand, a decrease in the system's performance has to be accepted.

Therefore, it is desirable that process, application, and technology-oriented knowledge is available in the state of design of the micro-system. To make this knowledge available, parameters of manufacturing processes are collected and stored in the knowledge database ProWiDa [1]. For this purpose a new modeling approach has been developed to allow for a

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full description of the key influencing factors in microsystem technology (MST). In the ProWiDa terminology, these factors are designated as technological aspects for the characterization of process related parameters. An analysis of the most influencing production factors led to the definition of five factors of influence for MST:

- Materials
- Procedure
- Geometry
- Machines
- Tools

Material, procedure, and geometry are almost sufficient for the definition of parameter sets relevant to the design engineer for realistic modeling. A schematic overview of the relations between the technology-oriented aspects and the subsequent technological properties is given in Figure 1.

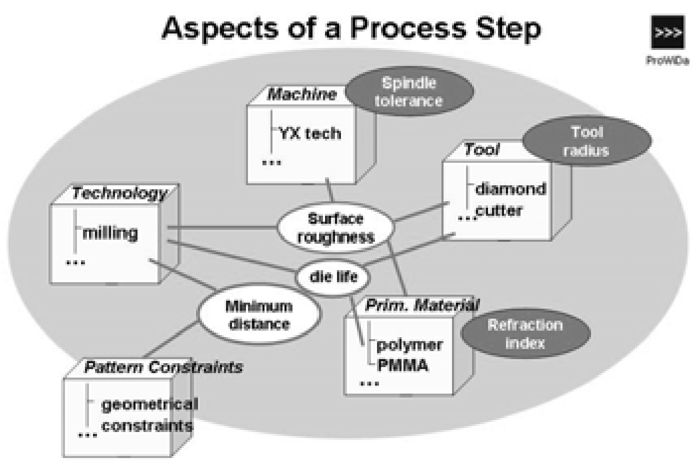


Fig 1. Correlations between technological aspects in ProWiDa

To fulfill the demand of linking technological aspects with the product requirements, not only a single specific aspect becomes of relevance. Furthermore, the combination of all aspects leads to a realistic view and allows for realistic modeling. This so-called competence consists of additional, more product-related parameters for the description of the resulting product properties. Besides the inherited aspect-specific values the competences are enriched with resulting application / design oriented parameters that are exclusively dedicated to the specific n-tupel of aspects. Due to the uniqueness of the specific combination, a competence is comparable to a company-specific design rule for a specific process step. For instance, the combination of a process, the material to be processed, the processing machine describe competences by the product property parameter "surface roughness".

The surface roughness parameter value need not result from the single master making or replication competence, it also can be influenced by additional coating process steps or other additional process steps. Consequently, design rules for a given task cannot be described in a static manner. The process database rather has to support the identification of a best fitting approach for a given task. For the reusable storage of technological know-how and the application- independent derivation of the resulting design parameters the knowledge of the relations and interdependencies of the process steps is of crucial importance.

The resulting design parameters serve as input in a comprehensive modeling approach:

1. On basis of the design rules the simulation model can be adjusted to the process chain.
2. On basis of the tolerance parameters tolerance compensation by means of the functional design can be achieved.
3. On basis of the material parameters analysis of operational and ambient effects can be carried out.

To predict the reliability of micro-systems in operation, it is not sufficient to only model and simulate the functional aspects of the systems. Environmental influences also have to be taken into account. A fluctuation of temperature, for instance, may affect the positioning of the individual components and, hence, the performance. And there may be influences resulting directly from the system's operation as well. For instance, heat generation of a laser source may cause a distortion of optically relevant surfaces or alignment structures. Consequently, it is necessary to consider effects of several physical domains in simulation. This requires the coupling of different simulation tools.

To solve the problems described above, optical functional components are combined with the mechanical structures (e.g. structures for alignment or mounting). These combined structures can be used to model not only the optical performance of the micro-optical subsystems, but also influences of the mechanical structures on the optical performance. This approach allows for an adaptation of the software design to application-specific problems like tolerances of the manufacturing processes, design for manufacturing, or consideration of environmental effects on the system's performance.

3. APPLICATION EXAMPLES

The following section will present three case studies to demonstrate use of the strategy described above:

- Robust design of an infrared (IR) gas sensor for CO_2 detection
- Design for manufacturing a micro-optical distance sensor
- Robust design of a lens of variable optical power (Alvarez-Humphrey lens)

3.1 Robust design of an IR gas sensor

Operation of IR analyzers is based on the absorption of certain wavelengths of infrared radiation specific to individual gases. In the wavelength range of 3.0-5.2 µm, the characteristic absorption bands of many gases and vapors allow to set up measuring systems combining an IR source, an absorption cell, a wavelength filter (or spectrometer, respectively), and a detector element (Fig. 2).

Fig 2. Schematic representation of an IR gas sensor

The absorption can be described as a function of the ray path in the medium to be measured, the type of molecule, and the concentration of a dissolved substance (Lambert-Beer law [2]). To detect of weakly absorbing gases, the optical ray path in the analysis chamber needs to be extended. If the geometric dimensions, which often are restricted, are to be retained, this can be achieved only by convoluting the ray path and adding additional reflecting elements. The integration of beam-focusing elements is becoming increasingly important in this connection to achieve sufficient loading of the detector. These beam-focusing elements are sensitive with respect to misalignment of individual components like e.g. the source or reflectors or other focusing elements. Figure 3 shows a test system of an IR gas sensor.

The gas analysis chamber assembled with detector and source is shown in front of the electronic interface. On basis of this test system first measurements for evaluation of the design were carried out with ambiguous results. The intensity distributions of two test measurements without sample gas are shown in Fig. 4. The result on the left hand side is obtained with a for optical maximum balanced chamber, i.e. the position of the source was actively adjusted until the maximum optical power was obtained. The irradiance distribution is as expected: a strong peak is clearly shown. On the right hand side of Fig. 4 a result of a simply assembled chamber is shown, i.e. no optical balancing was carried out while assembling. Here the irradiance distribution shows not the expected strong peak. The result is somewhat ambiguous and not usable for gas analysis. Investigation of the source, a simple light bulb, shows, that the position of the filament inside the bulb varies from sample to sample within a range of 1mm. This large inaccuracy of the filament's position prevents a reliable performance of the system and consequently makes a simple assembly process impossible. For this reason an active adjustment of the light source is necessary. However, active adjustment is not acceptable in a cheap production process, therefore a different approach has to be used: finding a new design of the focusing elements of the analysis chamber to compensate for the large position tolerance of the filament inside the bulb and make the design therefore rugged enough for a simple assembly process.

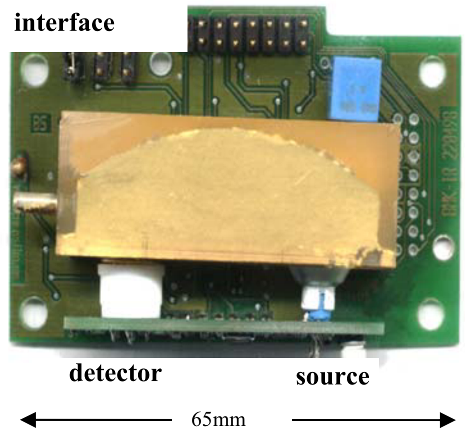


Fig 3. Photograph of a test system of the IR sensor and the controller interface.

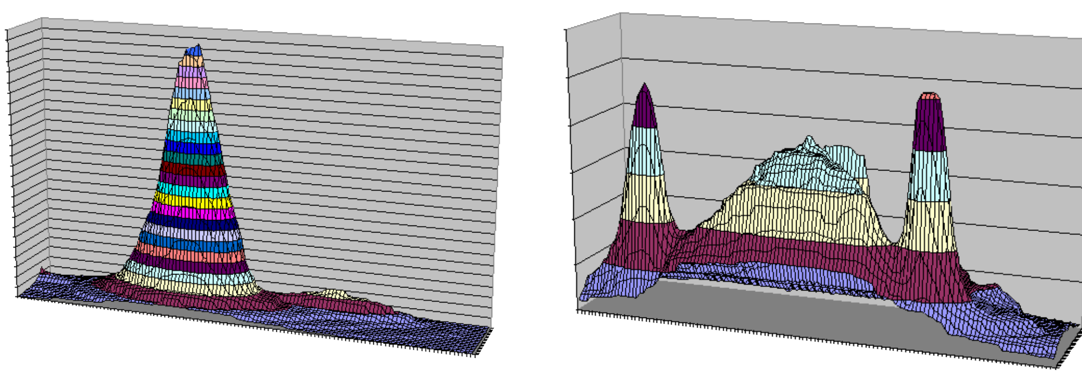


Fig 4. Irradiance Distribution original design: with balancing (left), without balancing (right).

To reach this goal, the original design has to be evaluated and structures sensitive to the source position must be identified. The following variables were identified for robust design optimization:

- The position of the reflectors to each other
- The curvature of the reflectors
- The source position

Boundary conditions included the physical dimensions of the chamber, the distance between source and detector, and the ray path inside the chamber. The design criterion chosen for optimization of the optical components was the maximization of optical performance in the total tolerance range of the filament in the light bulb of about ± 0.5 mm rather than maximization of the optical performance for ideal positioning. The result of this design process does not represent the best design of the optical components for an ideal arrangement, but the best design of the gas analysis chamber regarding the highly imprecise light source. The new design is fault-tolerant with respect to the position inaccuracy of the filament inside the optical source. Figure 5 shows the optical model of the analysis chamber.

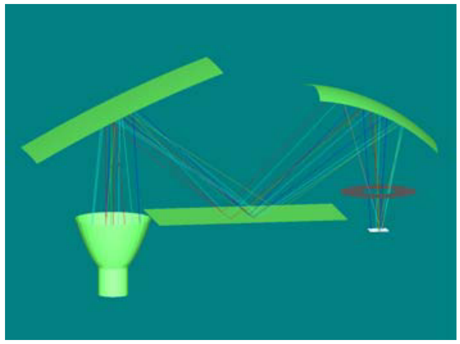


Fig 5. Optical model of the analysis chamber. Rays were traced for three different source positions in the tolerance range.

Figure 6 underlines this conclusion by showing the irradiance distributions of the optimized analysis chamber for ideal alignment (left) and a misalignment of the light source of about 3mm (right), i.e. three times the simulated position tolerance. Analyzing the two figures, two conclusions can be drawn:

- The distributions meet the requirements quite well.
- Even in case of a source misalignment of three times the simulated value, more than 60% of optical power hit the detector.

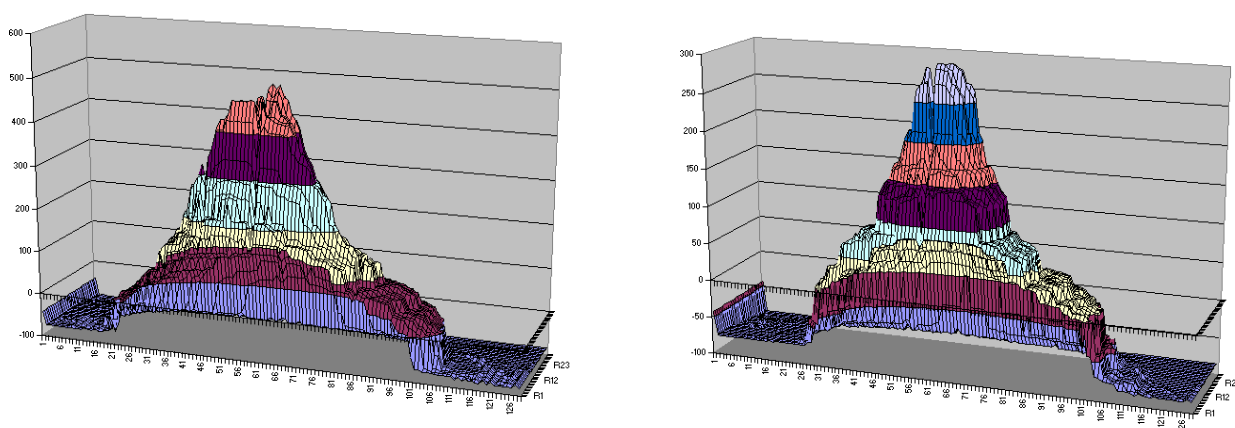
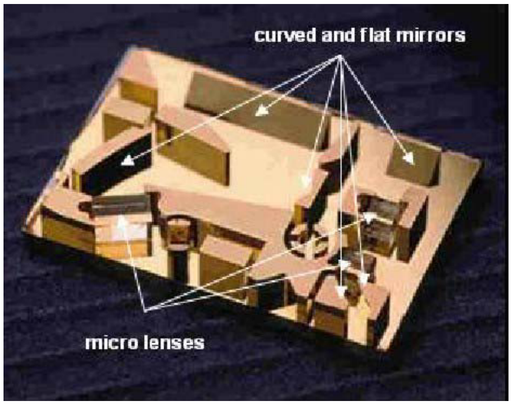


Fig 6. Irradiance Distribution optimised design: with balancing (left), without balancing (right).

The goal of the optimization was to find a rugged design regarding the position tolerances of the source. Use of the original design of the gas sensor requires manual assembly of the source by means of a power measurement. The optimized design ensures a well-defined performance over the entire tolerance range of the source position. This allows for an automated assembly of the analysis chamber.

3.2 Design for manufacturing of a micro-optical distance sensor

The micro-optical distance sensor is operated according to the principle of triangulation. The measurement range of the sensor in consideration is 10mm at a distance of 20mm with a requested resolution of 1/1000 of the measurement range. As detecting element a position sensitive device (PSD) was used. The sensor is set up in a modular manner, i.e. the passive optical part is separated from the electronics. This approach results in two subsystems: The first subsystem is called the micro-optical bench (MOB). The MOB is used to shape the light transmitted to the object as well as to collect the stray light from the object and to image it onto a detector. It is fabricated by micro-molding and consists of micro-lenses, curved and flat mirrors, separation walls as well as structures for the assembly of optical components to be mounted into the MOB. The second subsystem contains the active optical components and the electronics and is referred to as the electronic-optical board (EOB) (Fig. 7).



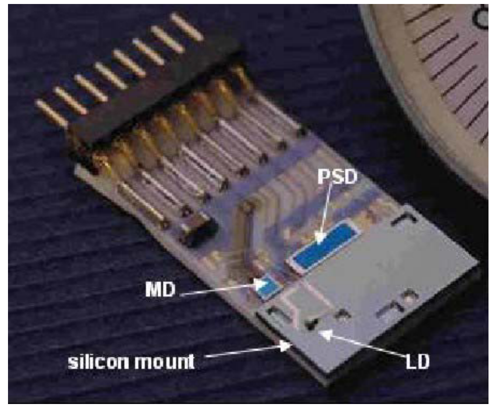


Fig 7. Micro-optical bench (MOB) of a distance sensor (left) and electronic-optical board (EOB) (right).

This modular design approach allows for a distributed fabrication of the modules at different manufacturers, with each one being an expert in the special technology needed for the fabrication of this module.

During the design phase, not only the optical specification of the sensor system but also all requirements given by the manufacturers, such as easy manufacturability with high throughput as well as defined interfaces, need to be considered. An extract of these requirements which result from the application of design rules determined by the individual process steps and the technologies involved are outlined in Table 1.

Table 1. Some design requirements for the micro-optical distance sensor. (e…electronics, fr…function and reliability, ha…handling/assembly, m…molding) [3].

requestor	requirements	motivation
fr	Free space for adhesive cavities for joining of EOP and MOB: 1.3mm x 0.8mm	To ensure the adhesion
fr	Marginal distances of adhesive cavities: 300µm	To advance the marginal rigity
fr	Release of the mirror structures	To avoid warpage of the optical structures
fr	Closed structures of the PMMA – boundary around the detection unit	Reduction of stray light
fr	Slanted wall structures (perpendicular to the substrate)	Suppression of parasitic light
e	Open marginal structures at the LD	Enabling of visual control of the bond wire
e	Openings in the back marginal structures	Free space for the PSD wires
m	Minimum distance between PMMA structures: 200µm	To ensure the demolding of the structures
m	Minimum wall thickness: 200µm	To ensure stability of the structures
m	Rounding of the PMMA edges	To ensure the demolding of the structures
ha	Free space for assembly paths	Enabling of collision free assembly
ha	Free space for mounting/alignment structures	Enabling the mounting of the optical components

The listed requirements arise of the fields electronics (e), function and reliability (fr), handling and assembly (ha), and molding (m). In consideration of these requirements the mechanical structures for positioning and fixation are designed and placed in the optical model. Thus the optical model of the micro-optical bench is expanded over the pure optical functions by adding the mechanical functions. In this way, optical design of the MOB does also cover process knowledge in the form of design rules and material parameters.

Knowledge of the material system of the MOB enables the designer to simulate environmental influences on the system's performance. Often, temperature variations at the place of operation have a distinct influence on the performance of a system. Since calculation of thermal loads on the structural components cannot be carried out by means of optical simulation tools a data exchange have to be implemented between the optical tool and a finite element method (FEM) tool capable of solving such problems. Results of the FEM calculations are geometrical changes of the optical components and their mounting structures due to a change of thermal load. These geometrical changes result in a deformation and a displacement of the optical components. Fig 8 shows the result of an FEM simulation of the MOB with the material parameter of polymethyl methacrylate (PMMA). Displayed is the displacement of the structure in z direction given in millimeters for a constant temperature load of 85°C.

The resulting data of the FEM simulation have to be retransferred to the optical simulation tool in order to determine the effects of the temperature load on the optical performance of the micro-optical subsystem. In a next step, optical analysis of the potentially deformed and misaligned optical functional structures can be carried out.

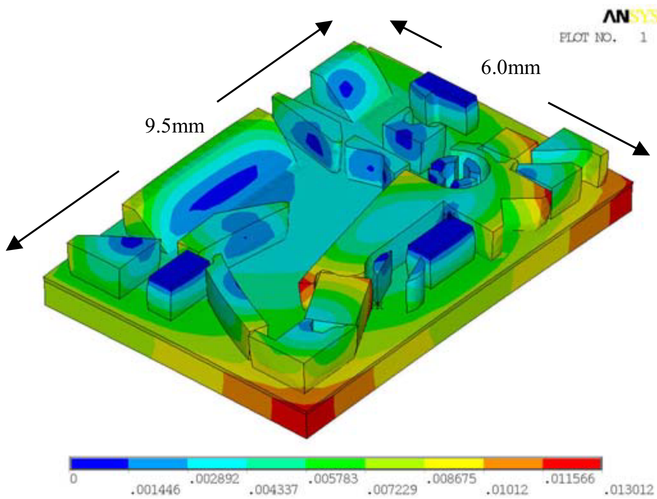


Fig 8. FEM-simulation of an MOB (PMMA) under a temperature load of 85oC (constant ambient temperature). The displacement values are given in mm.

In the here presented case study, two different materials were suitable for the hot embossing process used for replication: Polymethyl methacrylate (PMMA) and polycarbonate (PC). Four different constant temperatures (-40°C, 20°C (reference temperature), 60°C, 85°C) were used for the simulations. The deviation of the spot position on the PSD from the reference value in dependence on the temperature was used as criterion for nine equally spaced distances spanning the measuring range. Fig 9 displays the results of the optical analysis of an MOB manufactured in PMMA (left) and of an MOB manufactured in PC (right) at the above mentioned temperatures.

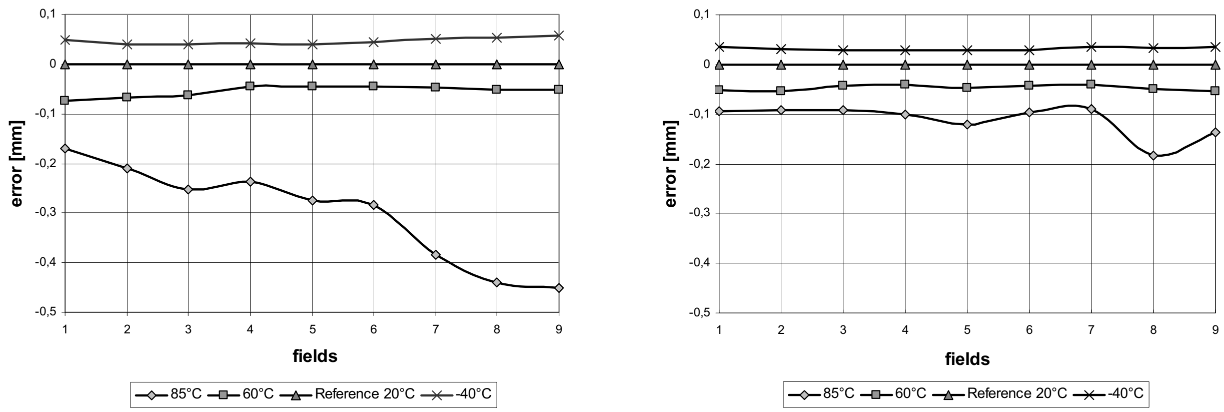


Fig 9. Error of the spot position on the PSD versus the fields, representing equally spaced distances spanning the measuring range for the two materials PMMA (left) and polycarbonate (right). Graphs are displayed for the temperatures -40°C, 20°C (reference temperature), 60°C, and 85°C.

It can be seen clearly that the error in the spot placement on the PSD is smaller for PC than for PMMA over the whole temperature range.

Consequently, the system's performance may be estimated for different materials in case of an ambient temperature variation as well as in case of influences resulting directly from the system's operation. With this knowledge, the right material can be chosen for the right field of operation and the desired performance of the system.

3.3 Robust design of a lens with variable optical power (Alvarez-Humphrey lens)

In the current trend of slim camera phones and miniature industrial cameras, miniaturizable lenses of variable refraction power are needed. Such lenses may also be used to restore the ability of accommodation of the human eye in case of presbyopia [4]. A promising concept of lenses of variable refraction power is the so-called Alvarez-Humphrey lens [5]. The Alvarez-Humphrey lens consists of two parts, the opposing surfaces of which are conjugated (Fig, 10).

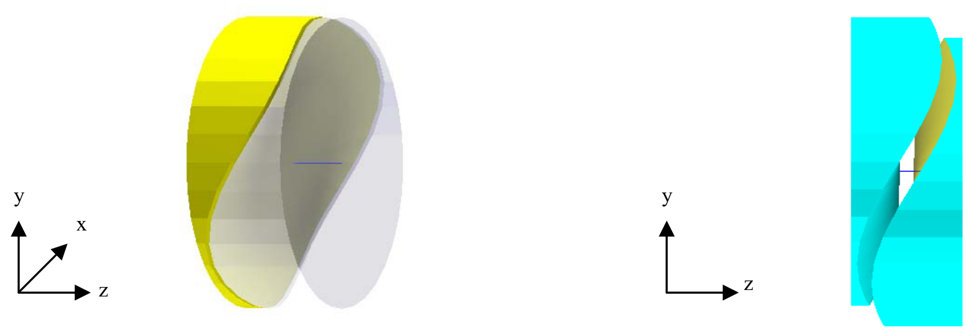


Fig 10. Functioning of an Alvarez-Humphrey optics with a variable refraction power.

Optical refraction power is varied by means of a lateral movement of the first Alvarez-Humphrey surface in y-direction. The relation between the lateral movement v and the change of refraction power ΔD is given by $\Delta D \sim A\ v$, where A is a parameter that determines the shape of the lens' surfaces.

To reach a good optical performance, both Alvarez-Humphrey surfaces must be adjusted well. An error in positioning these two parts may have a severe impact on the performance of the total system. Consequently, a tolerance analysis of the Alvarez-Humphrey optics is of great interest.

Three main types of assembly tolerances may be identified (Fig 11):

- Lateral position error in x-direction (Fig. 11, left)
- Wedge error (Fig. 11, middle)
- Orientation error (Fig. 11, right)

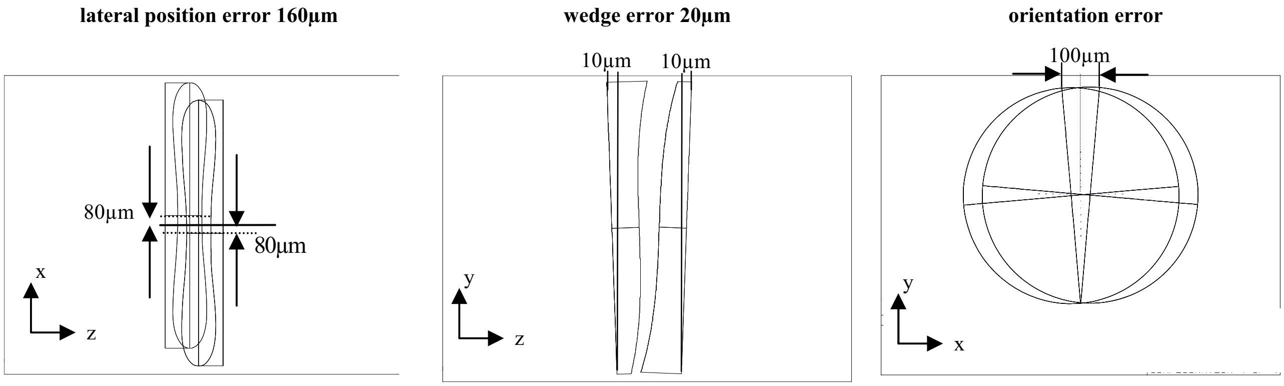


Fig 11. Different types of assembly tolerances identified for the Alvarez-Humphrey optics.

The first step in tolerance analysis is a so-called sensitivity analysis. The sensitivity analysis is used to investigate the influence of the individual tolerances on the evaluation criterion. As criterion, the modulation transfer function (MTF) is chosen. The MTF, also known as spatial frequency response, is a direct measure of how well the various details of the object are reproduced in the image. The MTF is well-established to specify and judge the optical imaging quality [6]. Figure 12 depicts the MTF versus the spatial frequency for the three different types of assembly tolerances identified and the reference (from top left to bottom right: Reference, lateral position error, wedge error, orientation error).

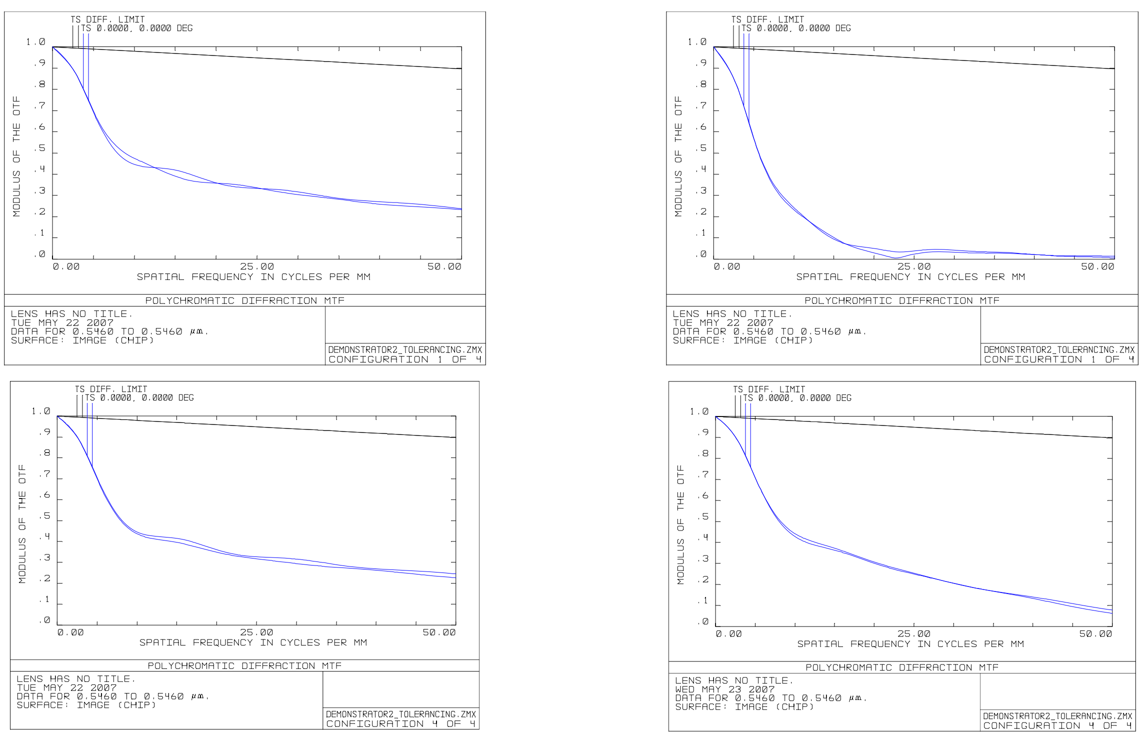


Fig 12. MTF versus spatial frequency for the three different types of assembly tolerances identified and the reference (from top left to bottom right: reference, lateral position error, wedge error, orientation error).

The lateral position error is identified to be the tolerance with the most severe influence on the system's performance. Due to this position error, the robust design approach is applied. A main feature of a robust design is that the optimization takes place over the total tolerance range. This approach results in a design that ensures a defined functionality with a minimum deviation of performance over the total tolerance range.

An analysis of the optimization with respect to tolerances yields the following results [7]:

- Slight improvement of the nominal value (by about 5.4%)
- Improvement of the worst value by 40.0%
- Improvement of the mean value by 10.7%
- Improvement of the standard deviation by 40.1%

It is clearly evident from the results that influences caused by manufacturing tolerances can be compensated by means of the functional design. An approach was developed and applied to compensate for assembly tolerances by means of the functional design of an Alvarez Humphrey optics. This approach consists of the following steps:

- Sensitivity analysis to identify the worst offenders
- Tolerance analysis on the basis of the Monte Carlo method
- Design optimization of the functional components

The result is a robust design with respect to the assembly process.

4. CONCLUSIONS

In the modeling and design of functional subsystems, the following aspects are considered to be of crucial importance:

- The model must be adjusted to the process chain. Design rules have to be taken into account.
- Manufacturing tolerances have to be considered in the design in order to compensate tolerances.
- Analysis of ambient and operational effects allows conclusions to be drawn with respect to the performance of the micro-system subject to different scenarios of ambient parameters and material.

The modeling approach was demonstrated for an IR gas sensor, a micro-optical distance sensor, and a lens of variable refraction power.

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