

Self-optimizing approach for automated laser resonator alignment

C. Brecher¹, R. Schmitt², P. Loosen^{3,4}, V. Guerrero¹, N. Pyschny^{1†}, A. Pavim^{2*}, A. Gatej³

¹Fraunhofer-Institute for Production Technologies IPT, Steinbachstraße 17, 52074 Aachen, Germany

²Laboratory for Machine Tools WZL, RWTH Aachen University, Steinbachstraße 19, 52074 Aachen, Germany

³Chair for Technology of Optical Systems, RWTH Aachen University, Steinbachstraße 15, 52074 Aachen, Germany

⁴Fraunhofer-Institute for Laser Technology, Steinbachstraße 15, 52074 Aachen, Germany

*Scholarship holder of the Brazilian CNPq

†Corresponding author: Nicolas.Pyschny@ipt.fraunhofer.de, Tel. +49 241 8904-164, FAX +49 241 8904-6164

Abstract

Nowadays, the assembly of laser systems is dominated by manual operations, involving elaborate alignment by means of adjustable mountings. From a competitive perspective, the most challenging problem in laser source manufacturing is price pressure, a result of cost competition exerted mainly from Asia. From an economical point of view, an automated assembly of laser systems defines a better approach to produce more reliable units at lower cost. However, the step from today's manual solutions towards an automated assembly requires parallel developments regarding product design, automation equipment and assembly processes.

This paper introduces briefly the idea of self-optimizing technical systems as a new approach towards highly flexible automation. Technically, the work focuses on the precision assembly of laser resonators, which is one of the final and most crucial assembly steps in terms of beam quality and laser power. The paper presents a new design approach for miniaturized laser systems, new automation concepts for a robot-based precision assembly, as well as passive and active alignment methods, which are based on a self-optimizing approach. Very promising results have already been achieved, considerably reducing the duration and complexity of the laser resonator assembly. These results as well as future development perspectives are discussed.

Keywords: Laser design, laser assembly, active alignment, self-optimization

1 Introduction

Laser and optical technologies are considered cross-sectional and key technologies with an increasing market demand in many distinct application areas (medical engineering, information technology, metrology, production technology etc.) **Fehler! Verweisquelle konnte nicht gefunden werden.**[2].

However, the assembly of laser systems usually is an expensive and challenging task, because these processes mostly consist of manual or semi-automated tasks performed by experts. Due to this fact, the assembly process alone is responsible for the major share of the product total costs. In a laser market with constantly changing output volumes and steady introduction of new product variants, increasing the degree of automation can only be economically viable if the efforts for changeovers, setups and reconfiguration of the production system can be reduced to a minimum. As such measures often increase the complexity and planning efforts of automated production systems, they can hardly be operated efficiently. Therefore, manual production tasks still remain as a widely spread alternative even in high-wage countries [2]. As a consequence, innovative solutions for flexibly automated assembly systems are required, which combine the advantages of automated processes with a maximum versatility.

Within the scope of the Cluster of Excellence research initiative "Integrative Production Technologies for high-wage Countries"⁽¹⁾, new strategies for the automated assembly of a miniaturized diode-pumped solid-state laser (called "MicroSlab") are under research and development. The main research focus is the application of self-

⁽¹⁾ See: <http://www.production-research.de/>

optimization principles in a flexible robot-based assembly cell, to develop solutions for an automated production of small lot sizes with high variance [4]**Fehler! Verweisquelle konnte nicht gefunden werden.**

In this paper, the concept of self-optimization will be derived from a theoretical definition and transferred to the specific application scenario of the automated resonator assembly of the MicroSlab.

First, the approach of a laser design for an automated assembly is presented, followed by concepts developed for self-optimizing automation.

The addressed assembly of the laser resonator shows challenges of unpredictable influence factors, e.g. from component tolerances, which can be overcome by means of adequate process strategies under integration of in-process optical metrology into the automated assembly process. Technical aspects of a passive and active alignment of the laser resonator mirrors are presented, which lead to promising results that can considerably reduce the duration and complexity of the assembly.

2 The MicroSlab laser and the laser resonator design

Classically designed laser systems are still being assembled manually since usually consisting of optical components mounted in adaptive lens holders. To fulfill the increasing demands on miniaturization and automation of the assembly, one approach is to omit lens holders and standardize the components' geometries respectively [5]. The MicroSlab laser design, as depicted in Figure 2 has been developed following the premises of planar technology.

The laser consists of a pump diode, some beam shaping optics as well as the laser resonator, comprising two mirrors and a Nd:YVO₄ laser crystal. The incoupling (curvature radius of 500 mm) and outcoupling mirror (plane) are forming a plano-concave resonator (see Figure 1).

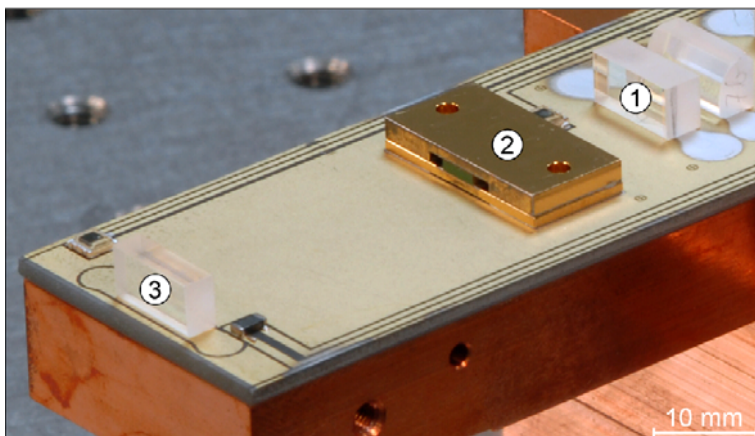


Figure 1: Laser resonator with incoupling mirror (1), Nd:YVO₄ crystal (2) and outcoupling mirror (3)

Although the resonator alignment belongs to the final assembly steps of the laser system, it is at the same time the most crucial part in terms of beam quality and laser power. Additionally, the resonator alignment is strongly influenced by prior assembly steps, since the positions of the beam shaping optics as well as that of the laser crystal define the boundary conditions for the alignment process. Hence, each laser system is individual, which means that no reproducible initial state can be realized for the assembly. Furthermore, placing the mirrors with a robotic system onto the best known positions cannot guarantee a resonant laser effect due to manufacturing tolerances of the components as well as the robot positioning imprecision (i.e. insufficient repeatability), which leads to the lack of a control variable when trying to optimize the mirrors' positions onto the value of the highest laser power. A common strategy to have a good starting position for the fine tuning of the resonator is to create an alternative control signal. This setup can be realized using a reference laser, which enables the referencing of all involved components, the mirrors as well as the crystal, to a common optical axis. Thereby, the incoupling mirror is referenced to the laser crystal and fixed by gluing or soldering. Afterwards the outcoupling mirror is referenced

to the incoupling mirror and subsequently its position can be optimized by using the laser power as a controlled process variable.

Using tolerance-associated components, the alignment could be sped up by gathering detailed information about each unique component and using simulation models to define their best positions. As the effort to characterize and measure these features for all components is unacceptably high, self-optimization of the alignment is a promising approach to reduce planning efforts and increase the efficiency of an automated assembly.

3 The concept of self-optimization

Self-optimizing production systems strive for a significant reduction of planning efforts within highly flexible automated systems, based on their high degree of adaptivity. By definition, self-optimization is characterized by the repetitive execution of [5][7]:

- 1) an analysis of the current system situation,
- 2) the determination of (new) system objectives, and
- 3) the adaptation of the system's behavior to the new surrounding conditions.

During the automated assembly of a complex and sensitive system, like the MicroSlab laser, unexpected situations occur frequently and would stop the execution of a strict automation procedure. Flexible assembly procedures, enabled through self-optimization, have the potential to resolve situations that require system adaptation and lead to a robust automated assembly.

An increased complexity of the resonator alignment results from high requirements on component positioning which have to be aligned under continuous observation, evaluation and optimization of laser output parameters. Process and component tolerances play an important role as every alignment starts with new and unpredictable conditions, requiring a self-optimizing process approach.

Thus, the self-optimizing alignment process has been designed as a two-stage process with:

- 1) A passive alignment of both mirrors by means of a reference laser beam;
- 2) An active alignment, where the laser is being switched on and the functional output of the system is being measured, evaluated and optimized.

Following the definition of self-optimization, the above three steps are executed repetitively during both alignments until the desired system status has been reached.

4 Automation concept

The approach for a flexible automation in precision assembly is based on large workspace positioning units (robots) which have insufficient precision (motion resolution) for the alignment processes described in [8]. For fine motion purposes, the robots can be equipped with a modular micromanipulator especially designed for the alignment of micro optical components. A prepositioning of the components can be performed with the robots within a large working area. After that, positioning errors are compensated and alignment movements are done by the micromanipulator. This results in a very flexible precision assembly system compared to classical Cartesian setups with precision axes and very limited workspaces.

The automation of the complete alignment process has been realized on a configurable assembly cell composed of three industrial robots with modular tools for executing and guiding the assembly tasks. The modular tools include – besides the micromanipulator – cameras, illumination, power sensors and soldering equipment.

For complex assembly tasks, e.g. the resonator alignment, two or three robots cooperate by carrying and positioning different necessary tools and sensors to execute and control the process (see section 5.2).

The micromanipulator for the high-precision alignment is based on parallel kinematics with six degrees of freedom and has been designed as a flexure-based monolithic structure (see Figure 2). By rigorous application of compliant joints, highest motion resolution can be achieved in all spatial axes. As miniaturized piezo-stepper motors are integrated for the actuation of the manipulator, nanometer steps can be resolved at the end effector with work space volumes above $3 \times 3 \times 3 \text{ mm}^3$. This allows for tilting angles of more than ± 5 degrees and angular steps of

0.3 millidegrees ($5\mu\text{rad}$) in the proximity of the neutral position of the mechanism. The manipulator itself has outer dimensions of less than a cubic decimeter and weighs around 250 grams.

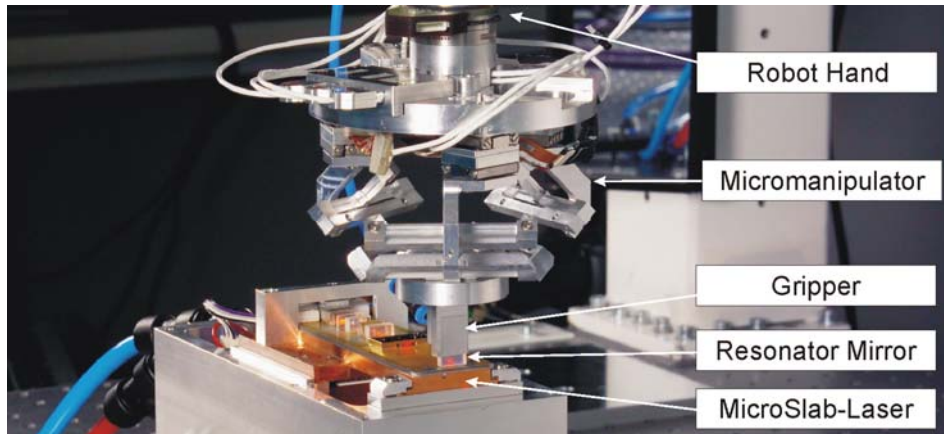


Figure 2: The micromanipulator and the arm configuration

5 Process design

As described, the alignment process has been designed following a self-optimizing approach and divided into two main steps: passive and active. For the passive alignment only geometrical parameters are taken into account, while for the active alignment, the performance parameters of the laser are continuously monitored in order to optimize the output power [9].

As a background for the process design, several manual experiments were performed, providing the necessary understanding of the practical challenges inherent to the resonator alignment.

5.1 Manual experiments

To analyze the resonator's sensitivity to changes in position of the outcoupling mirror, manual experiments have been conducted for both alignment processes. For this, all components have been pre-assembled and fixed on the carrier plate except from the outcoupling mirror, which can be aligned by means of an adjusting platform. A low power reference laser is pointed at the mirror being aligned, whose reflection is projected on a screen. By overlapping the reflections of the resonator mirrors, a pre-adjustment position can be defined. Subsequently the active alignment can be conducted, using an additional power meter that has been installed to measure the outgoing power as soon as the laser cavity is in resonance. Figure 3 states an exemplary pre-adjustment position after a manual passive alignment as well as a distribution of laser power as a function of yaw and pitch angles, interpolated from about 30 values. As depicted, a significant loss of output power already occurs for angular misalignments of less than 5 millidegrees (approx. $100\mu\text{rad}$), which underlines the need for high precision of the alignment tool as well as the subsequent fixation of the component.

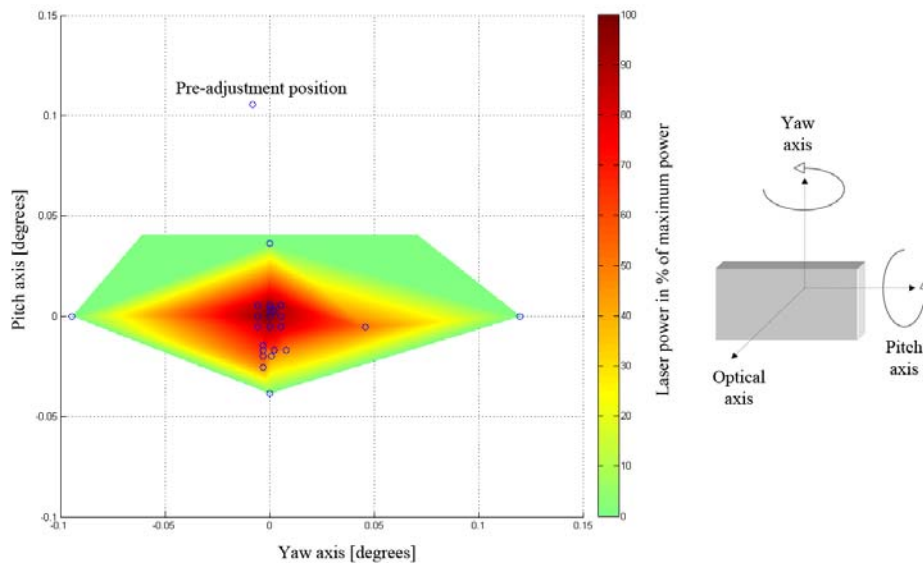


Figure 3: Interpolated laser power as a function of rotation angles of the outcoupling mirror

Multiple experiments of manually overlapping the reflecting spots of incoupling and outcoupling mirror showed that the passive alignment is practicable for a mirror misalignment below 100 millidegrees offset to the position of the maximum laser power. This deviation probably results from a certain visible resolution of the technician combined with a time-consuming iterative alignment process, but still this value stands for a good trade-off between precision and effort. In this context it can be expected that an automated algorithmic alignment can reduce this uncertainty, lead to a better initial condition for the subsequent active alignment and at the same time reduce alignment duration.

The manual active alignment on maximum output power has to follow the strategy of correcting the sensitive pitch angle to a local maximum and afterwards the yaw angle to the global maximum, since it is obvious that the sensitivity of the pitch axis is clearly higher than that of the yaw axis. This behavior can be explained by the geometry of the laser crystal which has an aspect ratio of 4 and leads to a similar ratio for the corresponding angles. Furthermore a possible tilt in the graph of the laser power behavior has to be considered during the maximum search, which is explicable by manufacturing tolerances of the crystal and its housing, as well as by a conceivable unevenness of the base plate and the solder. Taking the tilt combined with a certain response time of the power meter into consideration, a manual search for the optimal position can take up to five minutes.

5.2 Automated passive alignment

As described above, the passive alignment of the resonator is performed based on some geometrical aspects – specifically the parallelism of mirror and crystal surfaces – which can be made measurable by designing an auxiliary reference setup. This setup is based on a low power laser and an array of a mirror and a beam splitter. The main goal of the setup is to magnify the small changes in orientation of the mirror in order to make it measurable with a camera.

The camera is positioned by one of the robots in front of a visualization screen, on which the reflections of the crystal and the resonator mirrors are projected. In Figure 4, the position of the components and the path of the reference laser beam are shown. Considering the distance between the components, the resolution of the camera (8 megapixels) and the sharpness and roundness of the reflections, changes in orientation of about 2 millidegrees can be detected using this method.

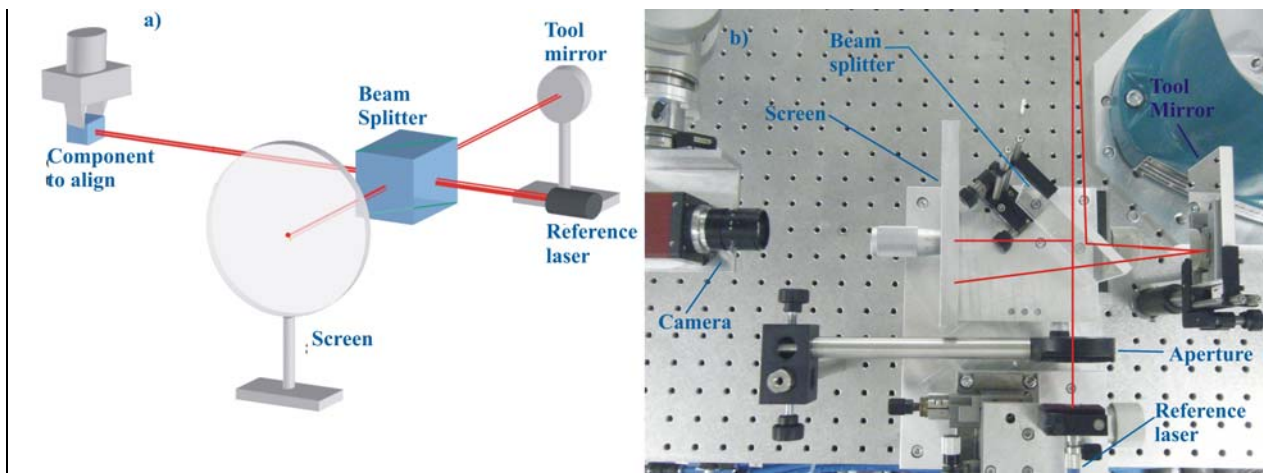


Figure 4: Misalignment measuring setup. a) Conceptual model, b) Real setup

During application, it is important to have all the optical components accurately aligned to a common means, i.e. the reference laser. This is done by firstly aligning the reference laser to the reflection of the front face of the crystal. Subsequently all further alignment operations are performed in reference to the optical axis of the laser. The actual alignment procedure at this point consists of placing the incoupling mirror at its predefined position and its approximated orientation. Then, the distance between its reflection and the one coming from the crystal is measured to obtain its angular misalignment based on image processing and geometrical calculations. This is done by comparing an image with the mirror reflection that is to be found and another template image of the reference laser beam previously saved (see Figure 5). This way the first mirror can automatically be aligned and then fixed to the laser baseplate. After the alignment of the incoupling mirror, its reflection and the one of the crystal are overlapping on the screen, and this point serves as the reference for the outcoupling mirror. The passive alignment of the outcoupling mirror is done in analogy to the first step. At the end of the passive alignment only one point can be seen on the visualization screen standing for the reflections of the three components overlapping.

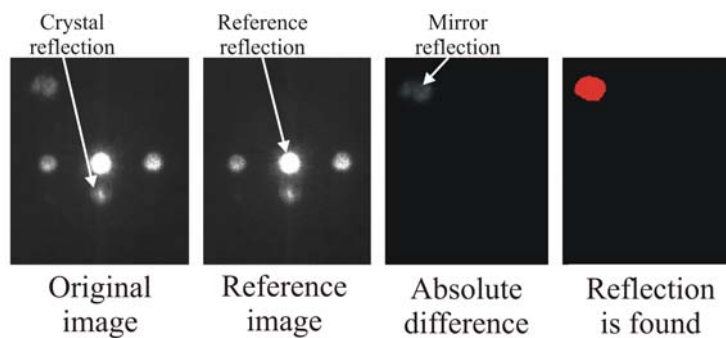


Figure 5: Image processing sequence

With the current setup dimensions, initial misalignments of around 2 degrees can be corrected, which are usually within expected tolerances. A larger initial misalignment of up to 4 degrees is still possible to be corrected, but an extra scanning sequence must be added to the automated alignment procedure in order to find the orientation in which the reflection hits on the screen.

5.3 Automated active alignment

The active alignment is the last step of the resonator assembly, consequently the final laser performance is highly dependant on the quality and success of it. The approach used for this purpose is the output power monitoring. Since this is a parameter closely related to the resonator parallelism, it can be used to guide the micromanipulator during alignment. For performing the measurement, a hot mirror is used to direct only the laser wavelengths (808 and 1064nm) onto the power meter. In this way, there are no obstacles for the reference laser used during the passive alignment.

Based on the manually conducted experiments and hence on the knowledge of the expected sensitivity, a grid consisting of approximately 150 angular positions has automatically been scanned to get a more detailed power distribution. In Figure 6a, the output power sensibility to resonator misalignment is presented.

Since the outcoupling mirror is a plan-plan mirror, only two angular degrees of freedom are highly sensitive to misalignment (see Figure 6), thus only the output power model for these two axes is obtained. Following the self-optimizing concept, the first step requires a deep understanding of possible failure states during the alignment procedure, whereby this information can be used afterwards to create a model, which the alignment algorithm can follow to reduce constantly the complexity of the alignment procedure.

A second factor considered for the alignment strategy design is the pre-alignment accuracy achieved by the passive alignment, which defines the size of the searching area in which the optimum orientation is to be found and consequently the number of output power samples to be taken.

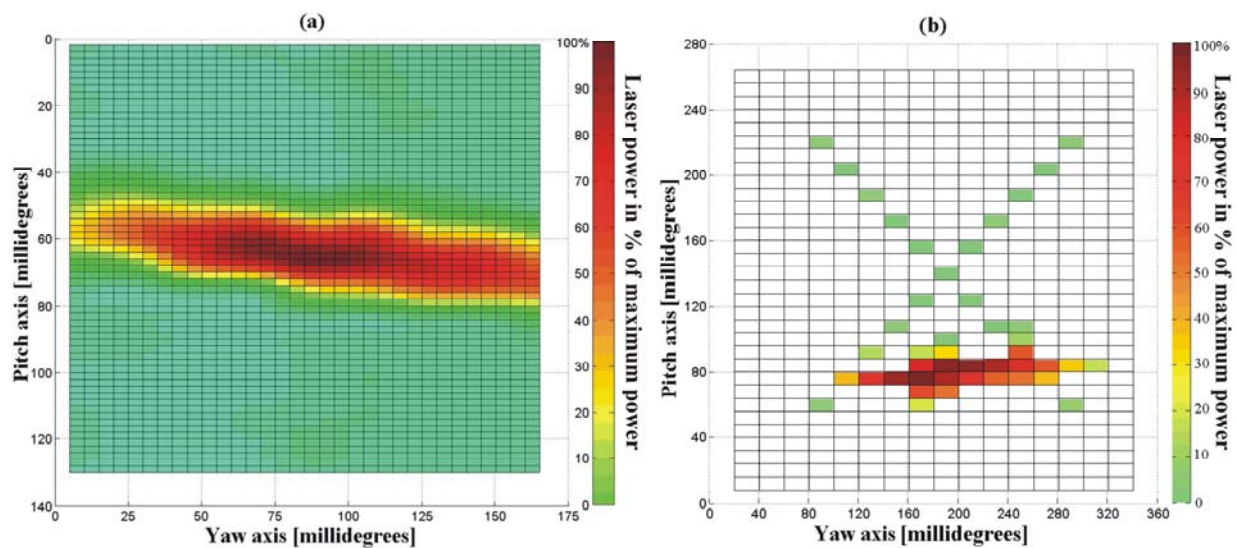


Figure 6: a) Output power sensibility to misalignments, b) “X” scan alignment example.

One simple strategy that has presented good results is based on performing an initial area scan with an “X” shape to locate in which orientation the laser resonator is well aligned and starts to show a positive effect on the output power. The convenient “X” shape allows to cover a large number of different orientations of the outcoupling mirror with a reduced number of necessary samples. Once a high output power orientation is found, the optimum orientation is only searched around that area following a gradient strategy iteratively in both axis. In Figure 6b, a resulting plot of a “X” shaped alignment procedure is shown. The advantage of using this method falls in the reduced number of samples necessary to find the optimum.

Another strategy that is currently in development and that also matches a self-optimizing approach is based on sampling the output power on a grid with just a few points, and then perform a regression to a parabolic surface similar to the real behavior of the laser. During the algorithm the mirror is moved in order to reach the maximum of

this parabola and afterwards get more points close to the alignment optimum. The model can then be continuously improved until the maximum of the parabola does not change significantly with each new sample. In Figure 7b, the parabolic model of the behavior of the laser is shown next to the real one for comparison (Figure 7a). The algorithm would only replace the gradient strategy from the “X” shape approach, since the initial orientation for approaching the resonator effect must still be located around the scanning area.

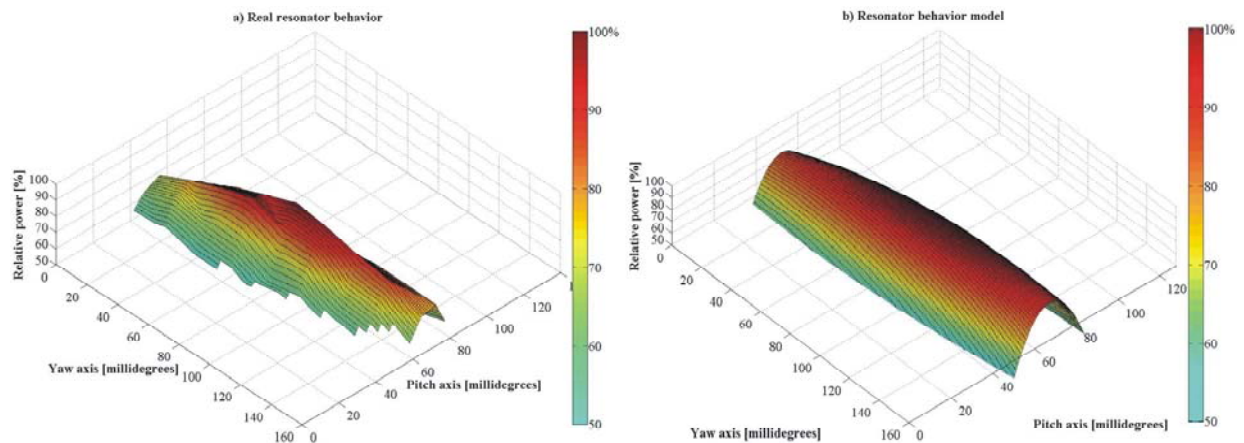


Figure 7: Comparison between measurement and model

6 Experimental results

The passive alignment presented an accuracy of approximately ± 35 millidegrees in both axes and thus a major improvement compared to the previous ± 100 millidegrees achieved by manual alignment. This value can be correlated with an unconsidered refraction in the beam splitter and the laser crystal itself. It is thus possible to improve this accuracy factor by considering the refraction aspect properly in the alignment calculations. Nevertheless, the passive alignment only requires only 4 to 5 seconds to be executed.

The active alignment showed a successful and robust performance, since it converged to the optimum in all the attempts, which consisted in executing the algorithm with different starting points around the scanning area. When using the “X” scan approach, the quality of the alignment can be improved consecutively just by adding new cycles with reduced step sizes. During the tests, it was empirically discovered that only two scans are enough to obtain almost the complete spectrum of the output power with a duration of approximately two minutes in each cycle. This time can still be reduced by using a fast response power meter.

7 Conclusions and perspectives

This paper presented briefly the design and assembly concept of the “MicroSlab” miniaturized diode-pumped solid-state laser and the experimented strategies for an automated and efficient alignment of the laser resonator mirrors. As the assembly of each new laser system is influenced by variable initial conditions and optical parameters, which cannot easily be compensated without considerable efforts for component characterization and assembly planning, a new approach of self-optimizing assembly and alignment strategies have been implemented. The conception of these self-optimizing automation strategies strives towards a compromise between an increased assembly flexibility and still low complexity and planning issues for assembly control.

The conception of passive and active alignment strategies, taking into consideration geometrical and performance features of the laser system respectively, enabled a very flexible and robust solution for an optimized alignment of the laser resonator mirrors. The mirrors are thus robustly aligned following a two-stage self-optimizing procedure, independent of the initial conditions of the system, defined by the positioning uncertainty of the robots or possible

deviations of the optical transfer function of the mirrors. A micromanipulator for the precise alignment of optical components and provides the basis for the implementation of the automated alignment.

The presented approach resulted in significant improvements compared to the previous manual or semi-automated procedures, such as a major reduction of assembly duration and an increased positioning precision, optimizing the final laser power characteristics to its maximum.

Future developments intend to optimize the design of the referencing and measurement setup, so that they can be integrated into the robotic cell without affecting or disturbing any other measurement or assembly procedure during the complete automated assembly of the miniaturized laser system.

Acknowledgment

The authors would like to thank the German Research Foundation (DFG) for the support within the Cluster of Excellence "Integrative Production Technology in High-Wage Countries" at the RWTH Aachen University.

References

- [1] R. Schmitt, A. Pavim, C. Brecher, N. Pyschny, P. Loosen, M. Funck, J. Dolkemeyer, V. Morasch, **Flexibel automatisierte Montage von Festkörperlasern**, in: *wt Werkstattstechnik online*, vol. 11, 2008, pp. 955-960
- [2] **Photonics 21, Lighting the Way Ahead – Strategic Research Agenda in Photonics, 2010, p.7**
- [3] K. Feldmann, **Montage-Flexibilität muss wirtschaftlich sein**, *Industrieanzeiger* 38/2007, 2007, p. 30
- [4] C. Brecher, N. Pyschny, P. Loosen, M. Funck, V. Morasch, R. Schmitt, A. Pavim, **Self-optimizing flexible assembly systems**, in: B. Klöpper, W. Dangelmaier, (Eds.), *Self-x in Engineering*, Paderborn, Germany: MV-Wissenschaft, 2009, pp. 23 – 38
- [5] M. Funck, J. Dolkemeyer, V. Morasch, P. Loosen, **Design of a Miniaturized Solid State Laser for Automated Assembly**, *Proceedings of the SPIE*, vol. 7721, 2010
- [6] U. Frank et al., **Selbstoptimierende Systeme des Maschinenbaus: Definition und Konzepte**, HNI-Verlagsschriftenreihe, Paderborn, 2004
- [7] J. Gausemeier et al, **A Design Methodology for Self-Optimizing Systems**, AAET 2005 - Automation, Assistance and Embedded Real Time Platforms for Transportation, 6th Braunschweig Conference, Technical University of Braunschweig, 2005
- [8] B. Siliciano, O. Khatib (Eds.), *Handbook of Robotics*, Springer, 2008, pp.424-426
- [9] M. Mohaupt, E. Beckert, R. Eberhardt A. Tünnermann, **Alignment procedures for Micro-optics**, in: Svetan Ratcher (Ed.), *Precision assembly technologies and systems*, Springer, Chamonix, 2010