Lasers in Manufacturing Conference 2021

3-dimensional beam shaping for dynamic adjustment of focus position and intensity distribution for laser welding and cutting

Jahn, Axel[a,*], Dittrich, Dirk[a], Börner, Stephan[a], Standfuss, Jens[a], Herwig, Patrick[a], Reinlein, Claudia[b]

[a]*Fraunhofer Institute for Material and Beam Technology, Winterbergstr. 28, Dresden 01277, Germany*
[b]*Robust AO, Kahlaische Straße 1, Jena 07743, Germany*

Abstract

Beam shaping, using highly dynamic beam oscillation, offers a high potential for the process control and thus the adaptation to specific process requirements. The realization of beam oscillation in 3 spatial directions opens up new possibilities for specific adjustment of the energy distribution in the melting zone and also creates prerequisites for high dynamic 3D welding and cutting.

A novel 3D optical system will be presented containing galvo-x/y-scanners combined with a new piezo-driven focus modulation (z-modul). This concept enables a synchronous high-frequency axis-control of the 3 spatial directions in a compact optics design.

In the lecture, construction concept and mode of operation of the 3D-system as well as achievable complex 3D energy distributions will be presented. Further, results of process investigations for welding Al alloys and 3D contours are shown and advantages in process stability and joint quality are derived.

Keywords: 3D beam oscillation; 3D optic; highly dynamic beam shaping; piezo driven moduls; focus adaption; material processing; laser beam welding

---

* Corresponding author. Tel.: +49-351-83391-3237
axel.jahn@iws.fraunhofer.de

1. Introduction and motivation

The use of scanner technology in laser material processing has experienced steady growth in the industrial environment in recent years. The reason for this is, among other things, complex 2D path contours that can be applied by fast beam manipulation without the use of expensive CNC axes. However, from a process point of view, the influence of the molten pool during welding or cutting is more interesting. This is associated with the possibility of adapting laser-based processes to the respective material or metallurgical characteristics (e.g. chemical composition, hot cracking), making them more process-stable and efficient. Since these possibilities focus only on 2D beam manipulation, active keyhole manipulation is not possible.

By extending the beam manipulation in direction of the beam propagation, the process field expands considerably. In case of laser cutting a spatial and time resolved energy distribution influences the cut front angle and gas kinematics for melt pool ejection. Process related parameters for laser beam welding such as the focus diameter not only allow a considerable influence on the welding or cutting process, but also the extension of the beam manipulation with respect to the welding contour. If this approach also succeeds with a significantly higher frequency than it is currently possible by using linear CNC axis, further simplification of the process control is possible. The reduction of expensive mechanical axis and thus of machine complexity also add to the advantages. In summary, the following key development areas can be highlighted.

- compensation of focal shift especially at high power application in macro material processes
    - thermal effects for complex transmissive optics e.g. large scale focusing optics for scanners
- focus sensitive processes due to short Rayleigh-Length, such as single mode laser processes
- change between keyhole welding and heat conduction welding
- compensation of keyhole instabilities and inhomogeneous melt pool flow (e.g. during copper welding)
- high reflective surfaces to adjust laser intensity and therefore beam coupling (start: high intensity; steady state: low intensity)
- component driven changes of contour welding or cutting
    - different z-positions for 3D components (fast working range movement), substitution of hardware CNC axis
    - a high dynamic focus shifting (fast actuator, low mass) compared to CNC axis
    - slope plane component position, reduction of hardware movement e.g. simplified robot path
- process interaction e.g. by keyhole expansion and active melt pool manipulation
- possibilities in case of laser cutting:
    - creating a large virtual Rayleigh length by smooth increase of focus diameter for large the process window
    - adaption of cut front to Brewster angle to increase absorption by scanning along feeding direction (x)
    - customized energy distribution on cut front by superposing a z-scanning to scanning along the feeding direction
    - optimizing ejecting gas flow by shaping the cut kerf width by perpendicular scan to feeding direction (y)
    - superposing X-Y-Z will achieve a mixture of described effects

2. State of the art

In the past different optic solutions have been developed to shift the laser beam in direction of beam propagation. Most of this approaches where done with mechanical movement of optic elements. That increases the size of the optics, makes them sensitive for misalignment and limits the z-scan speed of the system. However, different approaches have been used.

2.1. Current approach: passive / indirect focus adaption

When using X-Y scanners, it is usually necessary to influence the focus position during the scanning process in large working fields. Due to the rotation of the last scan mirror, the focus point moves on a radius around the tilt point of the mirror. This compensation can be realized by passive F-Theta optics. However, these optics only work in a very specific area (X-Y plane), and limit the scanning process to a two-dimensional plane. There are two basic types of F-Theta optics (Fig. 1). On the one hand, normal F-theta optics can be found on the market, in which the outgoing beam exits the optics at a variable angle. On the other hand, telecentric F-theta optics are used, in which the exiting beam is always perpendicular to the processing surface.

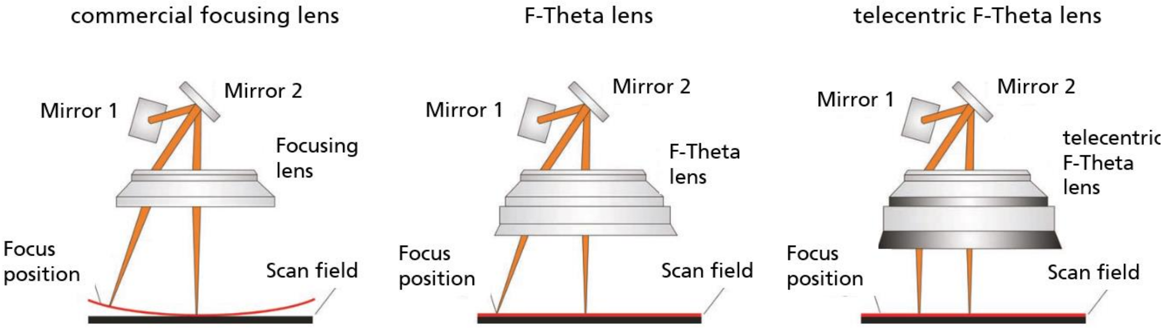


Fig. 1. optical configurations for passive / indirect focus adaption by [Bliedtner, 2013]

On the other hand using conventional optics parameter adjustment, such as power ramps or z-correction for focal shifting by machine axis can be used to compensate focal shift.

This welding solution could not be used for laser cutting. The distance between nozzle tip and work piece tip is an essential process parameter to eject molten material and to kept the quality constant.

In addition, the focus position control is needed to compensate for a physical effect, the focus shift. This occurs because the lenses in high power laser systems absorb a certain amount of power and establish a radial temperature profile that changes the lens parameter. As a consequence the focus position deviates with the laser power. Figure 2 shows a measured results of a laser-induces focal shift in a system with 245-mm focal length and a Rayleigh range of 0.7 mm. It is obvious that the system needs to be refocused with powers above 1000W. In the following, two principles of active focus position control are discussed.

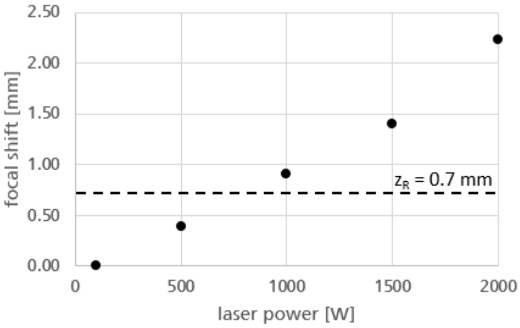


Fig. 2. Focal shift for selected laser powers with reference to the measurement at 100 Watts.

2.2. Hardware *approaches – active adaption of focus position*

Based on known technical approaches concerning the CO_2 laser, hardware solutions for shifting of the raw beam to ensure focus position, especially in large-format CNC machines, were used. These telescopic systems, adaptive mirror systems are controlled by compressed air. The stiffness of air limits the element dynamic and allows only stabilizing the spot diameter for the complete working field by shifting the beam waist of the raw beam.

Active process manipulation was not part of the concept. One property that can be assigned to modern piezo driven actuators is the dimensions less dynamic.

With the introduction of modern fiber lasers in material processing, other optical approaches had to be developed which, on the one hand, allow a wide control range of the optical beam manipulation and, on the other hand, are fast controllable and thermally stable. Piezo-driven optical elements represent a suitable solution, which can be controlled more easily and effectively, in particular by avoiding mechanical elements, see Fig. 3. The following technical characteristics can be summarized for these new systems:

- dynamic for high dynamic movement of focal position
- compact optical setup, easy to integrate in existing optics module frameworks

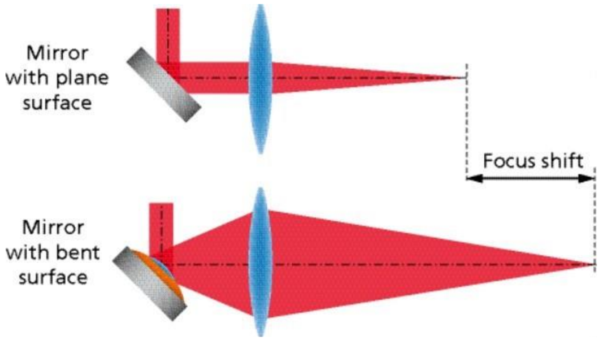


Fig. 3. Focus position manipulation by piezo driven optical elements.

Reviewing the state of the art, of often very expensive and complex approaches, piezo driven optical unit allow more options towards beam manipulation. The following conclusions and advantages of those systems can be addressed:

+ piezo driven optics are highly flexible and easy to control
+ better implantation into existing optic paths due to compact setup
+ high flexible in parameter adaption
+ one piece production easy to generate
+ cost effective compared to CNC-linear drives

Aspects that prohibited a wide range of industrial use of piezo driven optics are:

- integration level of established solutions – currently mainly piezo systems in lab use
- missing software HMI’s from established big supplier

Nevertheless, the intention of this paper is to use lab-adapted systems and to show first effects and process results using piezo driven units as standalone units and in combination with state of the art 2D optics. Therefore first results of fully 3D optics with respect to the process will be given.

3. Experimental setup

The experimental testing of a piezo driven mirror system usable for high performance processes is realized in two steps. First, the system is calibrated by the manufacturer and set up in the Fraunhofer IWS welding laboratory and the focus position shift was measured with a Primes MicroSpotMonitor. In addition, an exemplary welding test is developed to investigate and evaluate the functionality of the system. Subsequently, a commercially available 2D scanner is linked in order to create a 3D optic, see Fig. 4, which shows the schematic superposition of z-modulation with typical beam shapes of known 2D scanners to manipulate the weld pool.

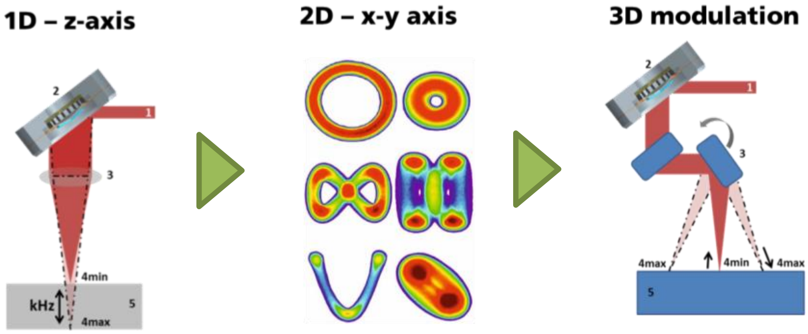


Fig. 4. Schematic beam axis movement concept explanation with laser beam (1), piezo driven z-mirror (2), focusing optics /scanner optics (3), focal position (4) and work piece (5).

In the following, the technical hardware solution is translated into an experimental setup using a single mode fiber laser (output power 1 kW). The control linkage of the single components is done by an in-house developed hardware, the ESL-2-100 module to ensure a fast signal control. The experimental setup shown in Fig. 5 is characterized again with respect to the beam guidance before process-related tests were implemented.

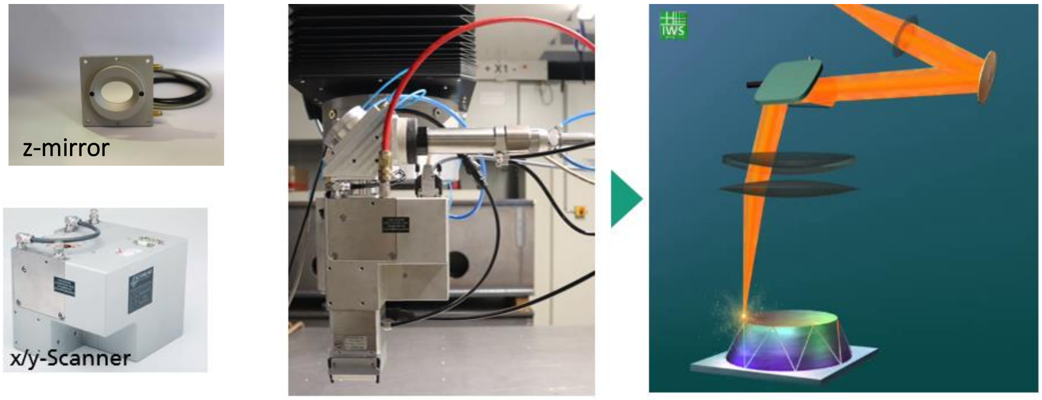


Fig. 5. Experimental concept explanation.

Furthermore, the technical data of the used equipment is presented in table 1. The system itself can be used with up to 6 kW laser power which is suitable for most of the technical application, such as electro mobility, automotive application and consumer product manufacturing as well as for difficult to weld materials. A potential transfer into real application is therefore not limited.

Table 1. Overview of optical properties for each optics element

Optics	X-Y Scanner	z-mirror	Laser source	YLS-SM
Wave length [nm]	1020 – 1080	1020 – 1080	Wave length [nm]	1070
Reflectivity	99.5%	99.99%	Maximum laser power [W]	1000
Free aperture [mm]	20,8	24	Core fiber diameter [µm]	30
Laser power, max. [kW]	6	6	Beam parameter product [mm mrad]	0.4
Step response [ms]	2,3 (10%)	2,0 (100%)	Collimation length [mm]	100
Scanning frequency [kHz]	4	1	Focal length [mm]	245
Amplitude			Focal diameter [µm]	33
scanning frequency = 2 kHz	± 3,1 mrad		Rayleigh length [mm]	1.5
scanning frequency = 4 kHz	± 0,4 mrad			
focus shift for different focal lenses:				
f_{foc}= 200 mm		+ 15 mm		
f_{foc}= 500 mm		+ 147 mm		

4. Results

Due to the extended optics configuration, resulting from the combination of z-mirror and x-y scanner, there are many possibilities for beam manipulation. To correlate the set scan parameters with process phenomena, an exact description of the beam caustics and the intensity distribution is required. In the following, the individual optical elements are measured first, followed by the effects of 3D beam manipulation.

4.1. Laser beam caustic measurement

Within the first measurement the focal shift of the z-mirror where measured at a constant laser power of 50 Watts. The calibration curve is used to determine the focus with the highest intensity and then to define the control variables for the exact setting of defined focus shifts, see Fig. 6. The static measurements is carried out for a focal movement of approximately 28 mm (+/- 14 mm) which is large range in terms of process parameters using one optics. The measured caustic is show in Fig. 6, right side. The obtained results correspond with the expected focal size from the theoretical correlation.

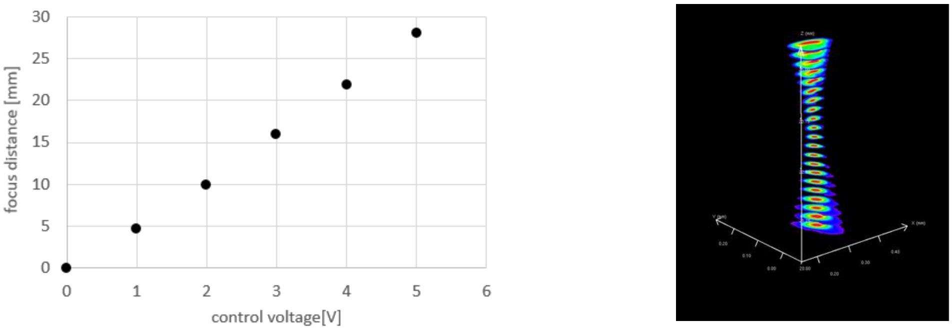


Fig. 6. Left: calibration curve of z-mirror; right: measured of intensity distribution for different focal positions.

The next step is referring to the dynamic movement of a 2D axis combination and a 3D axis beam manipulation. The dynamic measurement was performed by a synchronous 3D beam movement at 100 Hz to create stationary complex 3D energy distribution, which are possible with the designed optics configuration in the laser lab at Fraunhofer IWS, see Fig. 7. The configurations are the following:

- 1D-modulation (z-axis) to artificial **increase the Rayleigh length and focus range**
  - Target: stabilizing cutting and welding process
- 2D-modulation (y-z-axis) to design an **linear beam manipulation**
  - Target: customized energy input to cut front; shaping the key hole
- 3D-modulation (x-y-z axis) movement which describes a **circle-helix-shape**
  - Target: mixed optimization of cutting and welding process

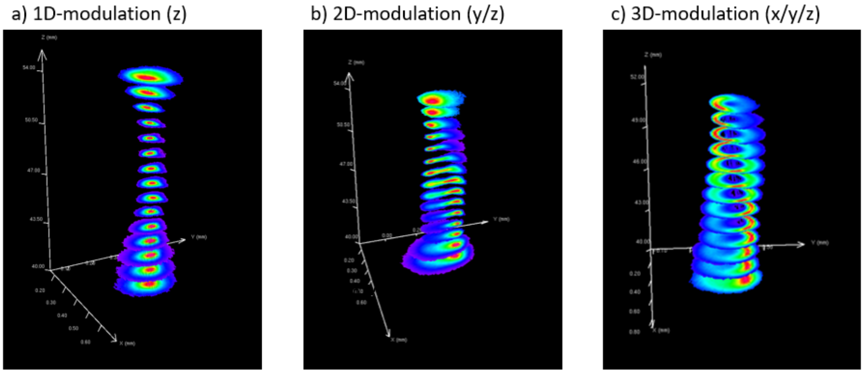

a) 1D-modulation (z)
b) 2D-modulation (y/z)
c) 3D-modulation (x/y/z)

Fig. 7. Overview: (a) measurement of intensity distribution for 1D-(z)-modulation; (b) measurement of intensity distribution for a 2D-(y/z)-movement different focal positions; (c) measurement of intensity distribution for a 3D-(x/y/z)-movement different focal positions.

4.2. Laser beam welding process results for z-oscillation

Further welding trials served to determine the influence of an additional variation of the focus position during welding with oscillation and constant power and speed. From the numerous cross-sections made, a significant influence on the weld penetration depth could not be demonstrated.

However, a look at the longitudinal sections resulting from the individual parameters, the influence of the oscillation becomes more clearly visible, Fig. 8. In the weld metal of the seam without beam oscillation there is a significantly larger amount of pores and the weld penetration depth varies greatly. The longitudinal section of the specimen with oscillation, on the other hand, shows a more homogeneous welding depth as well as significantly lower porosity.

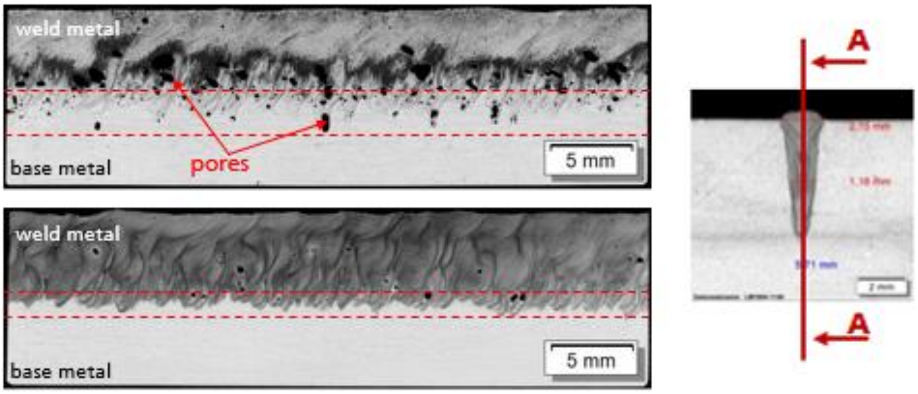


Fig. 8. Longitudinal cross section polishes: top: without z-oscillation; with overlaid z-oscillation in welding direction.

Accordingly, high-frequency z-oscillation can be used to reduce intensity peaks in the weld root. As a result, local evaporation (pores in the root area) and strong weld penetration depth fluctuations (spiking) can be significantly reduced.

4.3. Laser beam welding process results for the combination of x,y and z-axis modulation

Further welding tests have demonstrated the principle functionality of the integrated 3D optics, Fig. 10. The effect of the integrated focus tracking (z-axis) was demonstrated in comparative welds in sheet specimens inclined by 30° (with focus tracking: constant through-welding). On the one hand (without z-tracking) the process showed irregularities on the top of the weld seam and insufficient penetration on the root, Fig. 10, middle. Using focus tracking by modulation the laser beam in z-direction the differences in height of the welded surface where compensated, Fig. 9, right side.

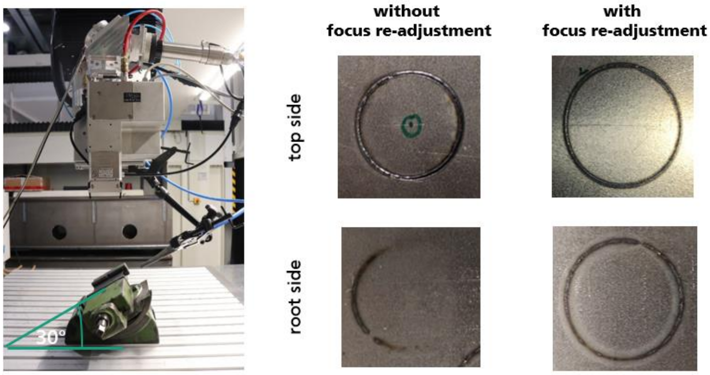
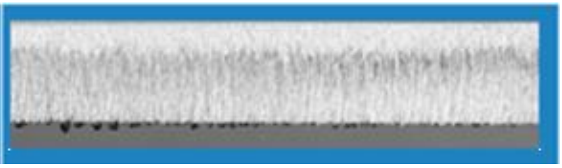


Fig. 9. Left: experimental setup for demonstration of the principle functionality; right: comparison of welding results without and with focus tracking.

4.4. Laser beam cutting first process results

The aim of the following process investigation was to achieve an increase in the feed rate with at least the same or better cutting quality. A focus position of 7.6 mm under the nozzle and a vibration frequency of 100 Hz at full stroke (measured 13.2 mm) were determined as the parameter set of highest performance. Comparable cutting qualities could be achieved with 0.8 m/min, which corresponds to an increase of 60 %. table 2 shows the improvements achieved by using adaptive optics compared to the reference.

Table 2. Results of the process investigation in flatbed cutting with 3 kW laser power, left: Reference cut with maximum performance, right: optimized cutting parameters with use of adaptive mirrors.

	
steel grade: 1.4301 / 10 mm tick	
Reference	z-beam oscillation
0,5 m/min	0,8 m/min
Focus position 6 mm below the nozzle	Focus position 7,2 mm below the nozzle
	100 Hz, 10 V, open loop

In summary, it can be said that process improvement is possible with the use of the adaptive mirror and oscillation. The potential is worked out using the example of a cutting application for 10 mm 1.4301 and a laser power of 3 kW.

5. Conclusion

A novel 3-dimensional fast beam-shaping module was developed and a prototype-optics was built and tested. The beam measurements demonstrate the feasibility of an intensity distribution that can be spatially adjusted within wide limits. This means that in the future the energy distribution in the effective zone can be specifically adapted to the prevailing conditions. This creates the requirements for shifting currently existing process limits to higher performance or better processing quality. The approach of integrated focal position detection also enables process-integrated real-time 3D-tracking of the focal position and can thus in the future compensate for the previously undefined thermal focus shift. The results can be concluded with the following bullet points:

- 3D beam modulation solutions for high performance laser beam welding and cutting processes
- focus shift adjustment possible – active control for high power application
- wide range of process parameter available to improve process stability for extension of process boundaries for difficult to weld materials
- Machining of 3D contours with real-time capable focus tracking
- Thermal focus shift control - improvement of machining quality
- Fast beam modulation for optimized energy input and increased process efficiency.

Acknowledgements

Basic developments for piezo-driven z-modulation have been carried-out in the project “smart^3 – PISTOL^3”, greatly funded by the German Federal Ministry of Education and Research (BMBF) within the incentive program “zwanzig20”. The manufacturing of the 3D-processing optics was realized in co-operation with the partner Robust AO.

References

Bliedtner, J.; Müller, H.; Barz, A.: Lasermaterialbearbeitung, Grundlagen – Verfahren – Anwendung – Beispiele. München: Carl Hanser Verlag, 2013

Böttner, Paul & Reinlein, Claudia & Jahn, Axel & Goppold, Cindy & Herwig, Patrick & Stoffel, Daniel & Bach, Mathias. (2019). Design, manufacturing and test of a highly dynamic piezo-driven metal mirror for laser material processing.

Jahn, Axel & Goppold, Cindy & Herwig, Patrick & Reinlein, Claudia & Böttner, Paul & Stoffel, Daniel & Bach, Mathias. (2019). High dynamic beam shaping by piezo driven modules for efficient and high quality laser beam cutting and welding.

Nair, Lakshmi & Goppold, Cindy & Böttner, Paul & Stoffel, Daniel & Jahn, Axel & Jolliffe, Cliff & Bach, Mathias. (2020). Piezo-based Beam Shaping for High Dynamic Three-dimensional (3-D) Laser Material Processing – PISTOL. Lasers in Engineering. 46. 305-312.