ELSEVIER
Available online at www.sciencedirect.com
SciVerse ScienceDirect
Physics Procedia 39 (2012) 800 – 806
Physics Procedia

LANE 2012

Focus alignment method for laser manufacturing at sub-micron positional accuracy

Johannes Strauß[a,c,*], Kristian Cvecek[b,c], Andreas Gröschl[a,b], Ilya Alexeev[a,c],
Michael Schmidt[a,b,c]

[a]*Chair of Photonic Technologies, Friedrich-Alexander Universität Erlangen-Nürnberg,Paul-Gordan-Straße 3,
91052 Erlangen, Germany*
[b]*Bayerische Laserzentrum GmbH, Konrad-Zuse-Straße 2-6, 91052 Erlangen, Germany*
[c]*Erlangen Graduate School in Advanced Optical Technologies (SAOT), Friedrich-Alexander-Universität Erlangen-Nürnberg,
Paul-Gordan-Straße 6, 91052 Erlangen, Germany*

Abstract

Accurate positioning of a sample is one of the major challenges in the laser micro manufacturing – especially if the requirements on tolerances are high as in ultrafast laser micromachining. There are a number of methods that allow detection of the surface position, however only few of them use the beam of the processing laser as a basis for the measurement. These methods have an advantage that any changes in the structuring beam will be inherently accommodated for. This work describes a direct contact free method to accurately determine the surface position with respect to the structuring beam focal plane. The method makes alignment of unique samples precise and time efficient due to ease of automation and provides a reproducibility of surface detection of less than 1µm.

Keywords: sample alignment; laser focus positioning; varying sample positioning

1. Introduction

Modern micro manufacturing processes normally require a high degree of precision in sample and/or laser focus positioning. The majority of surface structuring applications demands precise positioning of the laser focal spot on the working area as for ultrafast laser glass welding, for example [1]. In the latter case, displacement of the laser beam focus away from the common glass plate interface strongly reduces

---

* Corresponding author. Tel.: +49-9131-8523237 ; fax: +49-9131-8523234 .
E-mail address: johannes.strauss@lpt.uni-erlangen.de .

doi:10.1016/j.phpro.2012.10.103

mechanical strength of the joining seam produced during the ultrafast laser fusion welding [2]. Commonly used laser beam positioning techniques that are based on mechanical, capacitive and inductive principles, as well as optical solutions involving a pilot laser (e.g.: triangulation) may lack efficiency and accuracy since they are insensitive to any changes in the processing laser beam divergence/convergence or beam size variation. To achieve high positioning precision the system has to include the processing laser into the sample detection scheme. The most common positioning method works by structuring a sample stepwise at different focus heights. That, combined with a visual analysis of the produced structures (typically identification of the narrowest line), determines the proper focus height. There are a lot of variations of that method, but all of them are relatively labor intensive, difficult to automate, and produce undesirable reference structures. The nondestructive methods primarily use laser beam distortions for positioning, although it may degenerate the beam quality. For example, beam astigmatism is used for focus positioning in CD/DVD-ROM drives. For laser material processing this approach typically is not applicable since aberrated beams produce larger (and quite often asymmetric) focal spots with reduced peak intensities. In this publication, a nondestructive method to detect a workpiece surface assisted by the processing laser beam is reported.

2. Experimental principles

The principal idea of the proposed detection scheme is very similar to the basic setup of a confocal microscope (Fig. 1). In this arrangement the laser beam is focused by an optical element (typically a microscope objective) and the focused beam is partially back reflected by the workpiece. The reflected light is recollimated by the same optical element and partially transmitted through the dielectric mirror. Although modern laser line mirrors have very high reflectivity on the order of 99 % and higher, the weak leakage through the mirror (transmission) is sufficient to have a high signal-to-noise ratio on the sensor. The transmitted light is focused by another on-axis optical element (tube lens) to form an image of the focal spot on a digital sensor. The sensor is a digital camera, which can be seen as a 2D array of photodiodes equipped with small pinholes since the typical pixel size for modern cameras is ~5 µm or below. In order to mimic the confocal setup only the brightest pixel value is read. The described arrangement allows exploiting a very important feature of the confocal microscopy: shallow focal depth and as a result high axial resolution.

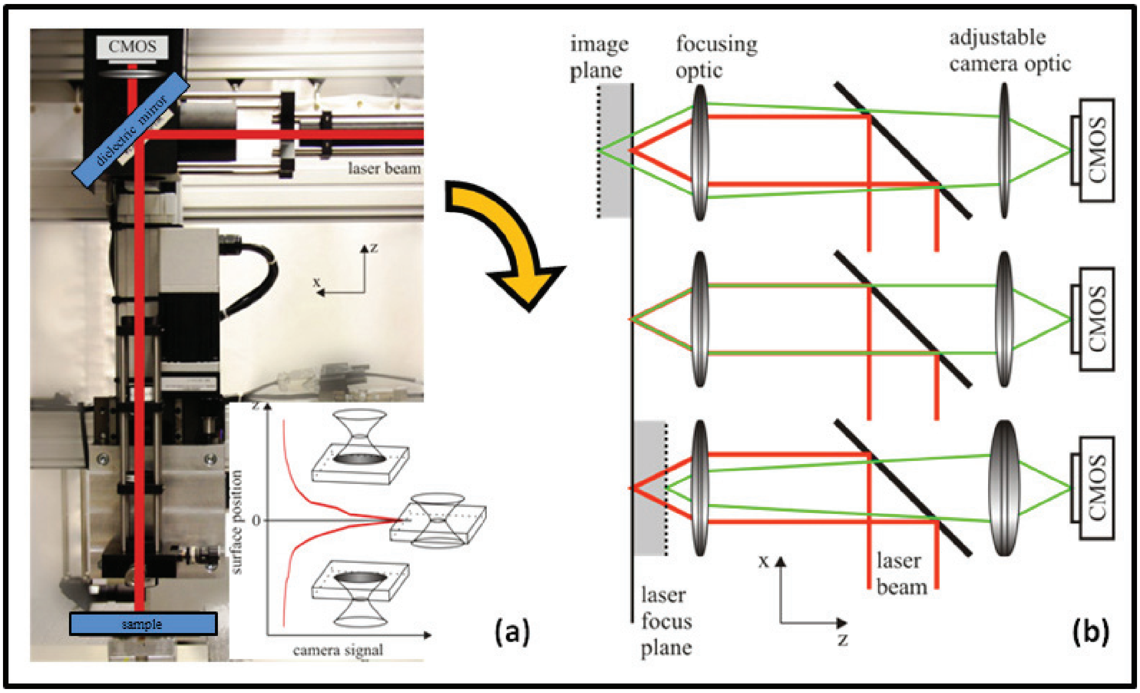

Fig. 1. (a) experimental setup; (b) principal diagram of the experimental setup rotated by 90o. The optimal configuration is in the middle, the upper and lower drawings show the mismatch between the focal and object planes. Position of the detected surface is somewhere in the gray area

By moving the workpiece longitudinally, the sensor signal as a function of the displacement can be read producing a characteristic curve shown in Fig.1a inset. The signal maximum corresponds to the focal spot being on the workpiece surface (desired position) and is clearly identifiable. In the experimental setup used for this work (Fig. 1a) a collimated 1064 nm wavelength laser beam ($1/e^2$ beam waist radius 1.5 mm) has been focused using a high NA microscope objective lens (Olympus LMPlan IT 50X / 0.55), reflected off the upper surface of a glass slide, recollimated with a commercial 75 mm focal length CCTV lens (Tamron 1A1HB), and detected with a uEye black and white CMOS camera (UI-1220SE-M-GL). The laser beam intensity is set to be significantly below the damage threshold for glass. In the given arrangements the workpiece is stationary while the focusing lens has been displaced. Since the lens translation range (1-5 mm) is orders of magnitude shorter than the Rayleigh length of the unfocused laser beam (~5 m), the beam size variation on the objective can be neglected. Although the described positioning method may have extremely high reproducibility (on the order of 300 nm or less) it has a weak spot: potential presence of a systematic error due to the mismatch between the focal plane of the laser beam (red rays) and the object plane of the imaging system (green rays) as it can be seen in Fig. 1b. To achieve a high precision in absolute alignment this systematic error has to be corrected and zeroed out. This can be done either via variation of the focal length of the tube lens or via changing its position with respect to the sensor. The latter is typically easier to accomplish from the engineering prospective.

3. Experiment

To quantify the effect of the focal and imaging plane mismatch on the surface detection we have measured the relative uncertainty in the sample surface detection as a function of the tube lens focal setting. The tube lens (Tamron 1A1HB) has been modified to achieve negative focusing ranges. The total range has been divided into 12 angular (not linear) equidistant focal positions (the lens with the marked focal range is shown in the inset Fig. 2) and for each setting the detected surface position has been recorded (Fig. 2). The focus position determined at marking m1 is set to zero.

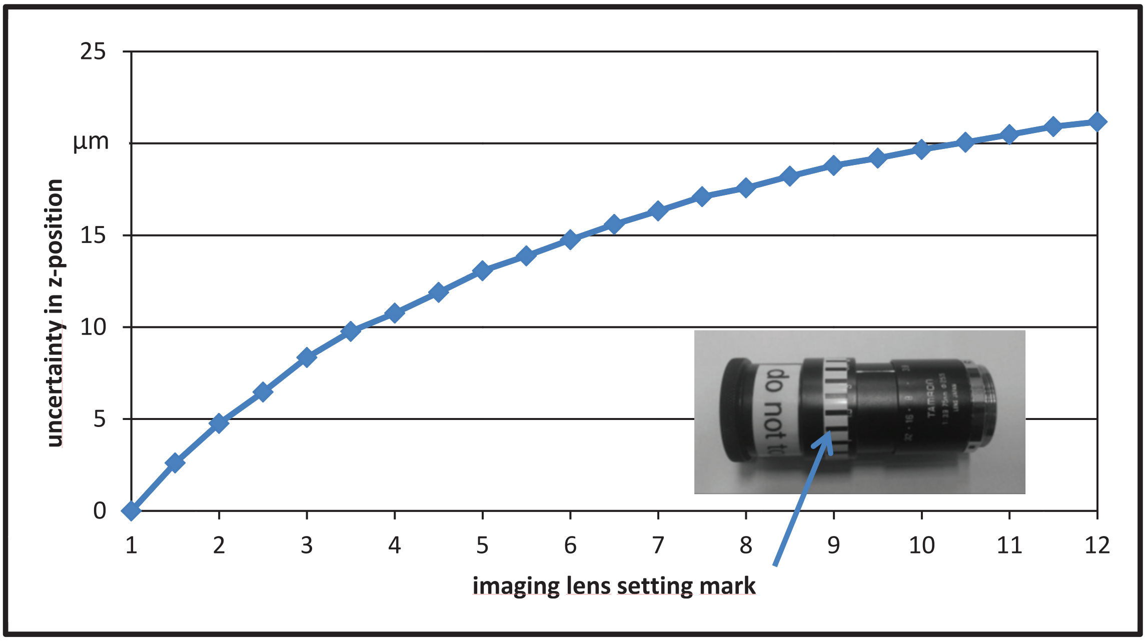

Fig. 2. Systematic error in the surface position depending on the tube lens setting. Inlet: modified imaging lens showing the markings

As it can be seen from the plot the differences in the detected surface position (between marking 1 and 12) is quite high ~25 microns, while the estimated Rayleigh range of the focused laser beam is significantly shorter ~10 microns. To achieve proper alignment the surface position should be detected at a precision less than the Rayleigh range. Due to the imposed tolerance the tube lens has to be adjusted with precision of approximately one division. In order to resolve the mismatch problem a consistent and reliable criterion for the tube lens alignment has to be established and applied.

To optimize the position of the imaging lens several approaches can be proposed. In the first method, a relatively intense laser beam is used to generate air plasma in the focal volume of the focusing lens [3]. By adjusting the position of the imaging lens the sharpest and the brightest image of the plasma ball can be optimized as shown in Fig. 3. The intensity at the camera senor and the spot diameter is represented here. At the bottom of the graph the images with respect to the markings are shown. It can be easily seen, that the best result is between marking 7 and 7.5. This method works straight forward and is reliable but requires very high laser intensities. To initiate air plasma high intensity on the order of 10^{13} W/cm² at the focus is necessary [6]. Therefore ultra-short pulsed (USP) lasers with short pulse duration (12 ps) and high pulse energy (15 µJ) combined with high NA (0.55) optics are necessary.

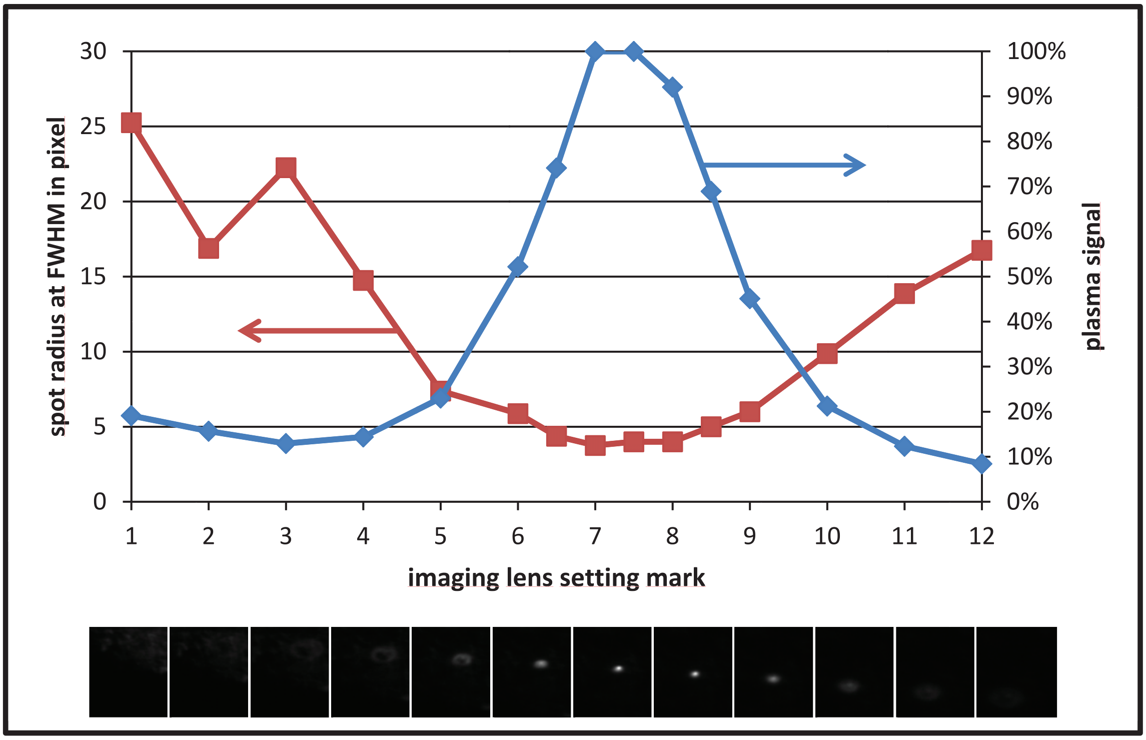

Fig. 3. Alignment by focusing image system to the "plasma ball" with spot radius at FWHM and intensity as indicators; the bottom line represent the images on the camera at the several markings

This high demand on a laser source and to the focusing conditions cannot always be fulfilled; in many cases these conditions are not even necessary for material processing. There the necessary intensities are one order of magnitude lower e.g. 10^{12} W/cm² at glass welding. When processing metal the intensity is much lower, typically at the level of 10^{9}-10^{10} W/cm² [4]. Additionally, this method is not feasible when samples are to be processed in vacuum or in noble gas atmosphere. Therefore another method to calibrate the setup is needed. In the following a calibration method is proposed that can greatly alleviate the requirements of the air-plasma method.

Our proposed method is based on the third harmonic generation (THG) at a glass surface which is described in [5]. Here, we use a transparent and polished glass plate (e.g. soda-lime-glass) to determine the offset (error) of the back reflection method. The glass plate is positioned perpendicularly to the laser beam as shown in Fig. 1a). The back reflection is measured in the already described way. As the laser beam (in our case at 1064 nm) passes the sample third harmonic (TH) radiation (at 355 nm) is generated at the surfaces. The direction of the radiation is approximately collinear to the incident laser beam. However, the THG is strongly intensity dependent, so that a substantial amount TH is generated only when the focus of the laser beam is in close vicinity of the glass surface. Since the signal is proportional to intensity on surface to the power of three the detection of the surface is much less dependent on any misalignment of the sensor or reimaging parameters. Due to the coherent properties of the surface generated TH it is easy to collect and monitor it by using a simple condenser lens (see Fig. 4). In order to measure only the TH radiation the primary wave(1064 nm) is filtered out by using a combination of a laser line mirror (that reflects 355 nm and transmits the primary wave) that is followed by subsequent 355 nm bandpass and 1064 nm notch interference filters. The TH radiation is detected with a camera device (UI-1245LE-M-GL) similar to the camera capturing the reflected signal. The ability of the filter and camera system to detect only 355 nm radiation was established by analyzing the signal in front of the camera by spectrometer.

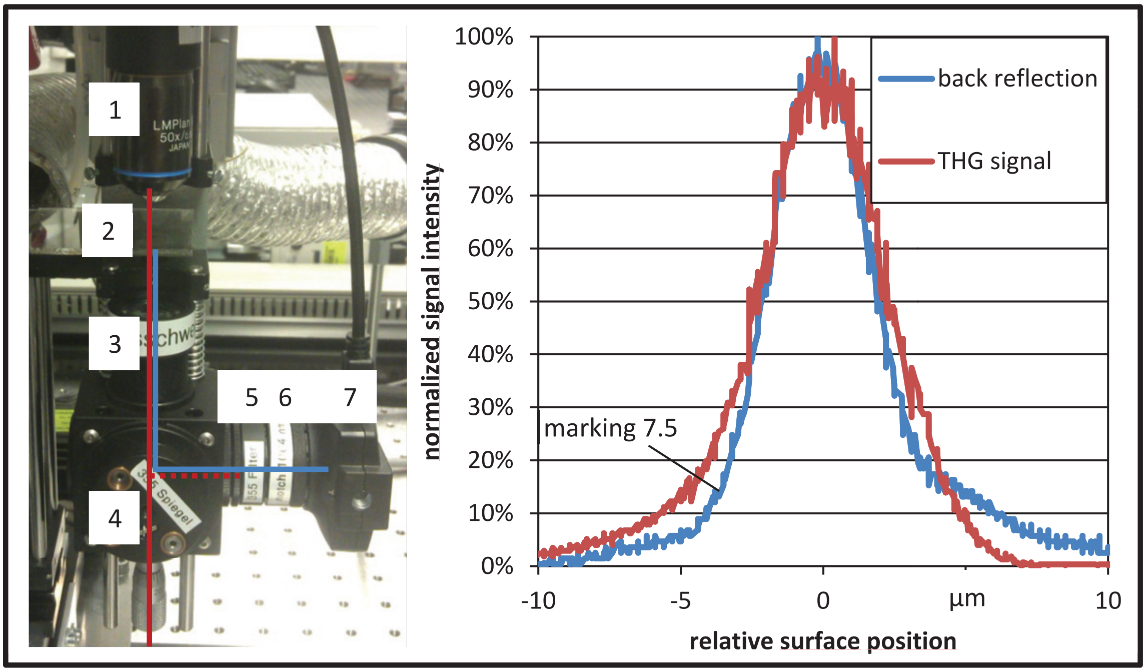

Fig. 4. Calibration via surface THG: left: setup of the sensor (1) Olympus IR focusing lens (2) glass sample (3) collimation lens (4) mirror reflective for 355 nm (5) pass filter for 355 nm (6) notch filter for 1064 nm (7) camera sensor equal to the sensor for the reflection signal. Right: simultaneous signal acquisition, reflected and THG to calibrate Tamron lens

The THG on glass surface occurs at relatively low intensities, for instance in this setup the necessary intensity is at 10^{11} W/cm². This is two orders of magnitude lower compared to the necessary intensity to produce air plasma at the same setup. These intensities are not sufficiently high to start plasma on the glass surface thus allowing for damage-free calibration or alignment of the focusing system. These properties of the surface THG make the method also applicable for ns-pulsed laser systems.

The plot on the right side of Fig. 4 presents the THG signal and the signal of the back reflection corresponding when the reimaging lens is set to marking 7.5. The effect of noise on the surface measurement precision can be reduced by fitting a Lorentz curve to the data. This corresponds to the results obtained by the plasma alignment method. The repeatability of surface detection is determined to be 100 nm. The THG signal was used to calibrate the back reflection module. The mismatch between the THG module and back reflection module was reduced down to 600 nm. This is a fairly large value when compared with the achievable repeatability. The reason for this originates in the manual adjustment of the imaging lens of the back-reflection module. However, this mismatch can be in principle reduced down to the achievable repeatability when an automated lens adjustment system is used.

4. Conclusion

A method to calibrate a confocal setup for surface detection has been introduced. This method is based on the third harmonic generation on glass surfaces. The reproducibility of absolute surface detection is 100 nm. The sensor constructed for this purpose can be easily used for surface detection or for the calibration of the confocal setup. The main advantage of using THG to detect or even calibrate a confocal setup is lesser demands on the laser source compared to plasma focusing. The THG positioning can be used solely or in combination with the back-reflection method for absolute sub-micron sample alignment. As the total accuracy of this method depends only on the Raleigh-length and the necessary intensities are far below the air plasma threshold the application of this method can be extended to ns-pulsed lasers which are much more commonly deployed in industrial environments.

Acknowledgements

This work was partially supported by the Erlangen Graduate School in Advanced Optical Technologies (SAOT), Friedrich-Alexander University Erlangen-Nuremberg.

References

[1] Alexeev, I.; Cvecek, K.; Miyamoto, I.; Schmidt, M.: Ultrafast Laser Processing of Transparent Media – Glass Welding. In: LEF 2010.

[2] Cvecek, K.; Miyamoto, I.; Strauß, J.; Bui, V.; Scharfenberg, S.; Frick, T.; Schmidt, M.: Strengh of Joining Seams in Glass Welded by Ultra-fast Lasers Depending on Focus Height. In: JLMN-Journal of Laser Micro/Nanoengineering, Vol. 7, No. 1, 2012.

[3] Xinbing, L.: Method and apparatus for determining focus position of a laser. In: Unites States Patent, US 6,303,903 B1, 2001.

[4] Häfner, T.; Reg, Y.; Hetzner, H.; Schmidt, M.: Mikrostrukturierung von Werkzeugstählen mittles Ultrakurzpulslasern. In: proceedings: LEF 2012.

[5] Tsang, T.: Optical third-harmonic generation at interfaces. In Physical Review A, Vol. 52 No. 5, 1995.

[6] Hügel, H.; Graf, T.: Laser in der Fertigung. DOI: 10.1007/978-3-8348-9570-7_3, Springer, 2009.