An improved approach for process monitoring in laser material processing

Hans-Georg König, Oliver Pütsch, Jochen Stollenwerk, Peter Loosen

Chair for Technology of Optical Systems, RWTH Aachen University, 52074 Aachen, Germany
Fraunhofer -Institute for Laser Technology, Steinbachstr.15, 52074 Aachen, Germany

ABSTRACT

Process monitoring is used in many different laser material processes due to the demand for reliable and stable processes. Among different methods, on-axis process monitoring offers multiple advantages.

To observe a laser material process it is unavoidable to choose a wavelength for observation that is different to the one used for material processing, otherwise the light of the processing laser would outshine the picture of the process. By choosing a different wavelength, lateral chromatic aberration occurs in not chromatically corrected optical systems with optical scanning units and f-Theta lenses. These aberrations lead to a truncated image of the process on the camera or the pyrometer, respectively. This is the reason for adulterated measurements and non-satisfying images of the process.

A new approach for solving the problem of field dependent lateral chromatic aberration in process monitoring is presented. Therefore, the scanner-based optical system is reproduced in a simulation environment, to predict the occurring lateral chromatic aberrations. In addition, a second deflecting system is integrated into the system. By using simulation, a predictive control is designed that uses the additional deflecting system to introduce reverse lateral deviations in order to compensate the lateral effect of chromatic aberration.

This paper illustrates the concept and the implementation of the predictive control, which is used to eliminate lateral chromatic aberrations in process monitoring, the simulation on which the system is based the optical system as well as the control concept.

Keywords: laser material processing, process monitoring, chromatic aberrations

1. INTRODUCTION

Process monitoring is an important feature of many efforts to preserve and improve the quality of laser material processing. Since it offers the opportunity to implement camera based feedback loops, it is widely used in processes where the position on the work piece is crucial for the process like in welding or structuring applications. Another important application of process monitoring is the detection of process errors.

For two-dimensional processing it is common to use scanning units to steer the beam by means of two rotatable mirrors. Since the region of interest shifts in these cases, it is necessary to adjust the observation angles of the camera or the pyrometer, if it is mounted externally. One speaks about coaxial beam monitoring when the processing beam path and the observation beam path are directed through the same optical element. This is done to save space and omit additional steering components.

In processes with scanning units it is common to use so called f-Theta lenses to focus the beam. F-Theta lenses, which can consist of one or more lenses, have two major characteristics. First, it compensates the field curvature that is introduced by the scanning unit. Second, it linearizes the relation between scanning angle and displacement.

For the integration of coaxial beam monitoring into a system, the laser beam is guided by a dichroic mirror before it reaches the scanning unit. This dichroic mirror is designed to deflect the wavelength of the laser beam and to be transparent for the wavelength of the observation beam so two paths are divided in this point.

*georg.koenig@tos.rwth-aachen.de; phone +49 241 8906-614; fax +49 241 8906-121
The light path of the observation wavelength is reversed compared to the beam path of the processing wavelength. First, the light passes the f-Theta lens, is deflected by the scanning unit, passes the dichroic mirror and is finally supposed to reach the detector chip or the pyrometer fibre (Figure 1). The critical point in this juncture is the f-Theta lens. Due to the dispersion that occurs in every optical glass, the observation wavelength is refracted in a different way and the optical axes of the laser beam path and the observation beam path do not coincide. Transverse chromatic aberrations arise leading to a truncated intensity profile on the detector. This effect is known and described in the literature [1,1,2] and axial chromatic aberration has already been used to control the position of the focal spot relative to the surface [3]. Since the intensity of the transverse chromatic aberration depends on the deflection angle of the scanning unit and therefore varies dynamically, it is not possible to compensate it with a passive optical element in front of the detector.

There are two solutions for this problem in the field of photography. The first one is the design of achromatic focusing units like it is state of the art in camera objectives. This approach is not persuaded since off the shelf f-Theta lenses are made for monochromatic laser applications and are therefore not chromatically corrected. Besides that the development and production of an achromatic f-Theta lens with its requirement for high aperture and high power suitable lenses made of glasses with specific dispersive requirements would come in very costly. A second solution is to eliminate chromatic aberrations with a software based approach [4]. In this approach the amount of chromatic aberration is computed by comparison of the red, green and blue channels of the detector and corrected in the digital picture. This procedure is not applicable in our case, due to the fact that the distance between the focusing unit and the detector is significantly longer in our application, compared to a camera, which leads to a truncation of the beam on the sensor or its complete miss.

A new approach is developed to solve the described problem [5]. By means of a second galvanometer scanner, the transverse chromatic aberrations are compensated in a manner that the beam path of the observation beam is guided to the center of the detector. Thereby, the amount as well as the direction of the occurring transverse chromatic aberration vary with the scanning angle but are rather predictable once the scanning angle is known. This is used to develop a predictive control for the second scanning unit in order to enhance the process monitoring.

![Figure 1: Schema of a conventional laser scanning unit (A) and a scanning unit with dispersion corrected coaxial process monitoring (B)](image)

2. SIMULATION

2.1 Simulation Set-Up

The goal of the simulation is to verify the possibility to compensate the transverse chromatic aberration introduced by the f-Theta lens by using a second scanning unit and to form a basis for the control of that scanning unit. In order to use the simulation data to control the experimental set-up the characteristics of the experimental set-up are used: A f-Theta lens with a focal length of 340 mm, a processing wavelength of 1.06 µm and an observation wavelength of 1.6 µm. For verifying the approach the simulation is also executed with the model of another f-Theta lens with a focal length of 126 mm as well as a variation of other processing and observation wavelengths.
The simulation is executed in two steps. First, the path of the processing laser beam is traced starting at the collimation unit followed by a dichroic mirror and goes through the scanning unit and the f-Theta lens up to the processing plane. The angles of the scanning mirrors are varied in fixed steps. Their values and the coordinates of the deflected beam are recorded. As a result, the combination of the scanning angles corresponding to a specific position in the processing plane for the chosen wavelength can be reproduced in a later step.

The source is modeled as a spot of 1 mm diameter representing the observed interaction zone. The location of the source in the processing plane and the values of the scanning mirrors are adapted to the values which have been recorded in the first step. Additionally, the wavelength is altered to the observation wavelength and the order of the optical elements is reversed. Figure 2 shows the observation beam path. Starting from the processing plane it traverses the f-Theta lens and is deflected by the scanning mirrors. Subsequently, it passes a focusing unit, consisting of three lenses for reducing the diameter of the beam. This way, it is possible to use a secondary scanning unit which mirror apertures are small compared to those of the primary scanning unit. The rays of the observation beam are deflected by the two mirrors of the secondary scanning unit and is coupled into a cylindrical glass body with a diameter of 200 µm. This is done in order to take the influence of an optical fibre into account as a fibre coupled pyrometer is used in the experimental set-up, see chapter 3.

An optimization function is implemented, which computes the mirrors’ angles of the secondary scanning unit to deflect the observation beam to the middle of the mimicked fibre. These angles are saved as well for being processed in the control unit.

![Diagram](image)

Figure 2: Simulation model of the observation beam path and detected spot at 0° and 8° deflection

### 2.2 Simulation results

The simulations show, that it is possible to compensate the lateral chromatic aberration that is introduced by the dispersion of the analyzed f-Theta lenses, by means of a second scanning unit. Figure 3 shows two exemplary parameter fields, where the deflection of the first and the second axis of the second scanning unit is plotted as a function of deflection of the processing beam in the processing plane. The mirror of the secondary scanning unit, which deflects the observation beam first, is referred to as the first mirror and the mirror, which deflects the beam second, as the second mirror, respectively.

Looking at the parameter field of the first mirror, which is colored red in Figure 3, it is notable that the values of the correction angles seem to build a skew plane. This is due to the fact that the first mirror has no influence on the correction of the lateral chromatic aberration that occurs if the processing beam is deflected in the X-direction. So the deflection values of the first mirror are just dependent on the amount of deflection in the Y-direction in the processing plane. However, the deflection values of the second mirror depend not only on the deflection of the processing beam in the X-direction, but also on the deflection of the processing beam in Y-direction. This is because the deflection of the second mirror is not independent from the deflection of the first mirror, which leads to the geometry of the parameter field of the second mirror.
colored green. This effect is well known in the literature and is often described in the context of distortion, introduced by galvanometric scanning units [6].

- Figure 3: Parameter fields of the first (red) and the second (green) scanning mirror, respectively of the secondary scanning unit as a function of X- and Y-deflection of the processing beam in the processing plane

3. EXPERIMENTAL SET-UP

3.1 Optical Path

A fibre laser source with 20 W power, a wavelength of 1064 nm and a M\(^2\) of 1.3 is used. The optical path consists of a collimation of 50 mm, which forms a beam of 5.5 mm diameter, a dichroic mirror, with a reflectivity of 94.4 % for the processing wavelength, a scanning unit with an aperture of 30 mm and a fused silica f-Theta lens with a focal length of 340 mm and a scan area of 210 x 210 [mm*mm].

The observation beam sees the optical elements in reversed order, as already described. At the dichroic mirror 99.0% of the observation beam is transmitted. Since it was the objective to use a small scanning unit for the correction of the chromatic aberration to save space and money, it is necessary to focus the beam before it reaches the second scanning unit in order to have small beam diameters on the mirrors. So a suitable focusing unit, consisting of three of the shelf components was designed. As the beam is supposed to be coupled into the fibre of a pyrometer an additionally optical probe is designed, consisting of three off the shelf lenses.

Figure 4: Photo of the experimental set-up with the f-Theta lens (A), the primary scanner (B), the collimating unit of the processing laser (C), the dichroic mirror (D), the secondary scanning unit (E) and the optical fibre that transports the heat radiation to the pyrometer (F)
3.2 Control

The scheme of the control is illustrated in Figure 5 and will be explained in the following.

The speed of the control is crucial since any delay, caused by the control would force the primary scanning unit and thereby the whole process to slow down. Therefore, a controller board is chosen whose core is a field programmable gate array (FPGA) (Xilinx XC6SLX45).

In order to keep the need for information, other than the optical set-up, at a minimum, only the angles of the primary scanning unit are needed as input. Hence, the function signal from the real-time control (RTC)-card, which is encoded in the XY2-100 protocol, is routed to the galvanometer mirrors of the primary scanning unit and additionally to the FPGA-controller. There, the 8-bit signal is decoded. Afterwards, the signal needs to be scaled to the angle range of the galvanometer mirrors, since the RTC uses the whole 8-bit range to address the mirrors’ positions.

Based on the saved simulation values of the primary and the secondary scanner angles a predicative control can be established. Therefore the two parameter fields that where gained in the simulation are used to compute the angles of the second mirror to the corresponding values of the primary scanner. Since the parameter fields consist of discrete supporting points, an interpolation has to be performed.

Due to the limited resources of the FPGA a bilinear interpolation is chosen for this purpose, since its ratio of accuracy to computing cost is a suitable trade-off. In this type of interpolation the four neighboring supporting points are taken into account and are weighted according to their distance to the input values [7].

After the angles of the two mirrors of the second scanner are computed, by means of the parameter field and the interpolation, they are converted into an analog signal in order to actuate the second scanner. As this scanning unit has a differential +/- 10 V input and the output range of the FPGA-board is 0-5 V, the analog output signal has to be converted with an analog circuitry.
4. CONCLUSION
The simulations show that it is possible to compensate not only the axial but also the lateral chromatic aberration by means of a second scanning unit. An optical system for this purpose has been designed and realized. Additionally, a concept for the control of the scanning units has been developed and implemented. The next step is the experimental validation of the simulation results and to test the limits of the realized system with regard to accuracy of the measured temperatures as well as the speed of the control.

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REFERENCES