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Acousto-optic pulse-selective laser beam deflection for micromachining with ultrashort pulsed lasers

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Abstract

Acousto-optic deflection of laser beams promises the opportunity of fast pulse-by-pulse deflection without negative effects of inertia of traditional galvanometer scanner systems. Despite being known for quite some time, integration of acousto-optic deflectors (AODs) in conventional ultrashort pulsed laser machines still seems to be sparse.
Our work addresses possible opportunities that result from the combination of AODs optimized for wavelengths of 515 nm and 1064 nm with traditional galvanometer scanner systems as well as pico- and femtosecond lasers of average powers up to 10 W and 25 W. Therefore, the development of an elaborated FPGA-based controller as well as an appropriate optical setup for the implementation into an existing laser machining setup has been investigated. Key has been the realization of sufficient interfaces and data processing structures in combination with a commercial controller system for new and accelerated laser processing strategies such as pattern or multi spot deflection for improved material processing.

Keywords: Acousto-optic; laser beam deflection; FPGA; ultrashort laser pulse micro machining

1. Introduction

Modern ultrashort pulse laser systems have evolved in recent years into sources of optical power with astonishing energy densities and repetition rates. A further increase of this performance in the near future is foreseeable. At the same time, the challenge arises to make the full potential of these laser systems available for laser material processing. Established beam deflection systems such as galvanometer scanners reach their mechanical limits when distributing the optical power provided, so that not every emitted pulse can also contribute to the actual machining process. Faster alternatives to available beam deflection systems are needed.

The use of acousto-optic components has been well established in laser technology for a long time. The effect of diffraction of light by acoustic waves is used today in numerous laser systems, among other things, for fast modulation or deflection of laser power. For materials processing using ultrashort pulse laser systems, more and more publications are emerging that incorporate acousto-optic components as independent functional groups for fast beam deflection, promising significantly reduced material processing times. The combination of conventional galvanometer scanner systems with acousto-optic deflectors (AODs) offers the possibility to counter the growing discrepancy between the mass-related inertia of mirror-based deflection systems on the one hand and ever higher repetition rates of modern laser systems on the other hand. The advantage of the large deflection angle range of galvanometer scanner systems can be combined with the advantage of high deflection rates of AODs.

The question of how the advantages of AODs can be made available to existing laser processing systems and how they can enable novel processing strategies remains essentially unanswered. Not only many technological aspects and challenges have to be solved like interface adaptations, real time processing and high frequency generation with low latency. More important seems to be a lack of awareness of possible benefits arising from the use of AODs by upcoming possibilities due to new processing strategies. This paper provides a first overview of an approach to integrate AODs individually or in combination with a galvanometer scanner into a conventional laser material processing setup. Using a controller system developed for this purpose, laser pulse-synchronous deflection is enabled.

2. Functionality of an acousto-optic deflector

Acousto-optical components consist of optically transparent materials such as quartz or TeO_2. Fig.1 displays the basic structure of an acousto-optic deflector.

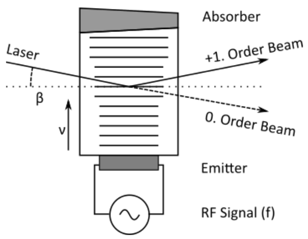

Fig. 1: Structure and function of an acousto-optic deflector.

A piezoceramic high-frequency emitter oscillating at frequency f is attached to one side of the optical body and generates sound waves in it which propagate with sound velocity v. Opposite to this, an absorber is attached, which suppresses the back reflection of the input sound wave. From an optical point of view, the propagating sound wave causes the formation of a volume grating. If laser power enters the optical medium at an angle β to the acoustic wave and fulfills the Bragg condition according to equation 1 with respect to the grating, the reflected optical components are constructively superimposed in higher diffraction orders.

$$\sin\beta = \frac{\lambda f}{2\,\nu} \tag{1}$$

Therefore, the deflection angle β becomes, at constant optical wavelength λ of the incident laser beam, dependent on the frequency f of the sound wave in the interaction area. For the use of AODs within material processing operations, diffraction into the first diffraction order is of vital interest.

3. Experimental setup

To enable pulse-synchronous laser beam deflection with high repetition rates in laser material processing systems using AODs, a stand-alone and modular controller based on an FPGA was realized. Fig. 2 shows the controller in front and rear view.

Fig. 2: Front and rear view of the controller for controlling the acousto-optical deflectors.

The use of individual hardware modules and dedicated IP cores makes it possible to adapt the controller to existing setups and to combine different data sources such as galvanometer scanners, linear axes or laser systems. Information processing is performed along a pipeline existing in the FPGA so that the acquired information can be evaluated and processed with low latency. For the operation of the AODs, the controller contains independent high-frequency generators.

For the strategies described below, a typical setup for laser material processing was used, which is outlined in Fig. 3.

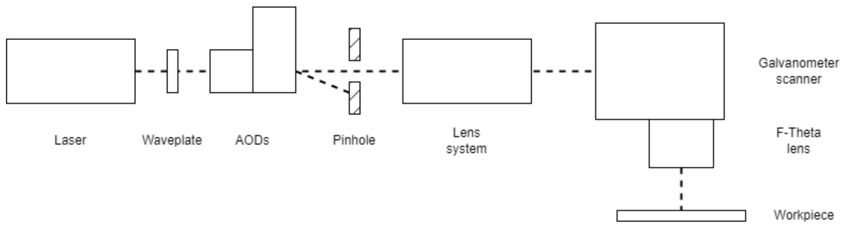

Fig. 3: Schematic representation of the optical setup used for the processes demonstrated in this paper.

The laser source is a Hylase 25 from neoLASE (wavelength 1064 nm, pulse duration <20 ps, repetition rate up to 40 MHz, pulse energy >125 µJ, average power >25 W, M^2 <1.3) whose emission is first aligned using a λ/2 waveplate. Subsequently, the deflection is performed by a pair of AODs of the type DTSXY-400-1064 from AA Opto-Electronic. While the 0th diffraction order is blocked behind the AODs, the 1st diffraction order propagates first through a lens system, through the following galvanometer scanner of the type hurrySCAN 14 of the company Scanlab and finally through a telecentric F-theta lens of the company LINOS with a focal length of 100 mm to the working plane. For the operation of the galvanometer scanner a control card of the type RTC4 of the company Scanlab is used.

The controller shown above is connected to the laser system, the RTC4 card and the AODs to acquire status information and control the process flow. In this configuration, the controller can read the data stream from the galvanometer scanner system, forward it to the scanner head, or intervene in the data stream. For the operation of the pair of AODs, two high-frequency amplifiers of the type AMPA-B-34-20.425 from AA Opto-

Electronic are used, which are inserted between the inputs of the AODs and the outputs of the high-frequency generators in the controller.

A structurally similar setup exists additionally for a center wavelength of 515 nm, whose laser source is a Pharos PH2-20-2000-10-C6-SB from the company Light Conversion (wavelength 515 nm, pulse duration <190 fs, repetition rate up to 1MHz, average power >15 W, pulse energy <=1 mJ, M^2 <1.2). In this paper, however, the focus is on illustrating the infrared setup presented.

4. Use cases and examples

Three process examples were chosen for the possibilities arising with the help of the controller, which will be shown in the next subsections.

4.1. Pattern based processes

With the help of the controller, an evaluation of data streams to and from conventional scanner heads becomes possible. This offers the chance to use AODs as a replacement for galvanometer scanner systems. Conventional software made for scanner-based laser material processing can be used as user interface. At the expense of a reduced working area, laser processes can be realized with adapted path planning, which do not have the disadvantage of the mass inertia of mirror systems. This can be particularly advantageous for processes with numerous and fine structures, where the share of acceleration and deceleration phases in the total process duration is predominant. Fig. 4 shows an example of a complex trajectory. The outlines of the logo were vectorized in a post-process and imported as a contour into the program SAMLight from the company SCAPS. In this, the graphic was scaled and transferred to the RTC4 board for process control. The developed AOD controller decodes the recorded data packets and sends corresponding control signals to the AOD system.

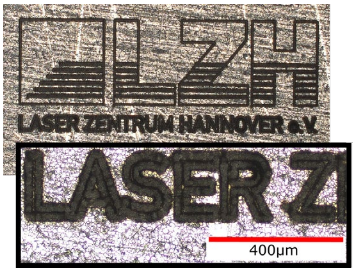

Fig. 4: AODs as a replacement for a galvo scanner. Lasered logo with detail display. Entered bars correspond to 400 µm.

Qualitatively, it stands out that the ablated pattern appears in uniform pulse spacing along the paths and without overshoots due to inertia. The duration of the deflection process was optimized by setting the deflection speed as well as the unavoidable system delays to their maximal respectively minimal values possible. Since this configuration overcomes the challenges posed by the inertia of the mirror system, deflection rates at the limit of the available data rate can be achieved. It also follows from this that by minimizing jump durations, a significant increase in the use of the laser power provided can be achieved. However, this process is still limited in speed by wait states resulting from conventional path planning and the limited data rate of 100 kspots/s and per channel. So the process heavily depends on the strategy used for path planning.

4.2. Pattern based processes

For effective deflection of the provided laser power using AODs, it would be desirable to operate the laser source continuously and to be able to assign a discrete deflection angle to each emitted laser pulse. This process, known as random-access scanning, can be implemented using the controller by synchronizing it with the laser system. The synchronization of laser emission and processed structure data then makes it possible to realize quasi multi spot processes. As an example, a process for percussion drilling of hole patterns in stainless steel (1.4301) is shown here in Fig. 5. While the mirror system remains in a center position, the two AODs drill 400 holes in a square grid. Here, the laser emits at a repetition rate of slightly above 100 kHz and the distribution of pulses is done synchronously (100 kspots/s). By deflecting all available pulses, a process duration of 3.86 ms per iteration (one pulse per hole position for all 400 holes in random order) is achieved.

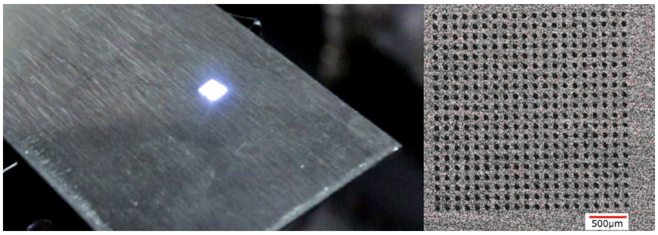

Fig. 5: Generation of a drilling pattern with 400 positions from single pulses using the AOD system. (a) Active machining process; (b) Resulting drilling pattern after 10 laser pulses per hole (10 iterations)

Furthermore, the application of the random access scanning method shows the possibility of realizing a laser process in which the full potential of the laser source used can be exploited. The possibility of determining the position sequence can also influence the input of heat into the work piece to be machined. For a uniform entry of heat, for example, a stochastic distribution of the pulses over the processing area can be made.

4.3. Combination of AODs and galvanometer scanner

The combination of galvanometer scanner systems with AODs offers the possibility to use the advantages of both systems for material processing. An example is the creation of a complex groove structure. While the large scanning area of the mirror system is used to move the laser focus in groove direction, one axis of the AOD pair is used to generate the depth profile perpendicular to it. During one run of the process, the distribution of power is also performed pulse by pulse with the laser source activated throughout. The depth structure is determined by the pulse distribution along the AOD axis. Fig. 6 shows the process as well as the machining result which can be obtained in a single galvo scanner path in groove direction.

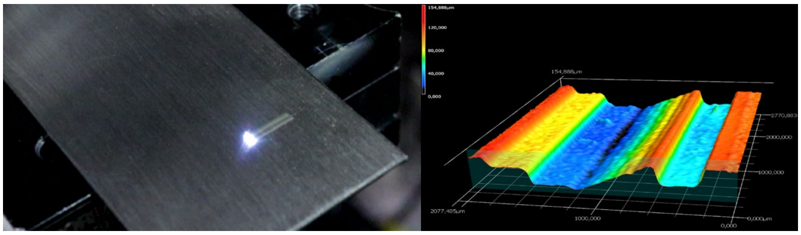

Fig. 6: Generation of groove structure by superimposing beam deflection by galvanometer scanner and AOD. (a) Active machining process; (b) Resulting depth profile of the groove.

It is evident here that the depth profile of the groove appears discrete, since each pulse is entered stationary by the AOD. Thus, for example, along the ramp-like structure the discrete sub-gradations stand out clearly. Here, too, the full potential of the laser source can be exploited with appropriate process planning and deflection can be performed pulse by pulse. In particular, it becomes possible to assign not only a position but also an intensity to each laser pulse. The process demonstrated could thus also be realized with the aid of pulse-synchronous intensity control.

5. Conclusion

In this paper, a controller for the integration of AODs into a conventional setup for laser material processing was presented and possibilities for its use for novel process strategies were shown based on selected examples. However, with the information and results presented here, it is already apparent that the use of AODs, in combination with conventional deflection systems, can lead to a significant expansion of the process possibilities and, in particular, to better utilization of the available power of modern laser systems. It has also been demonstrated that the integration of AOD systems into existing laser material processing equipment is possible with only minor modifications to the setup.

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