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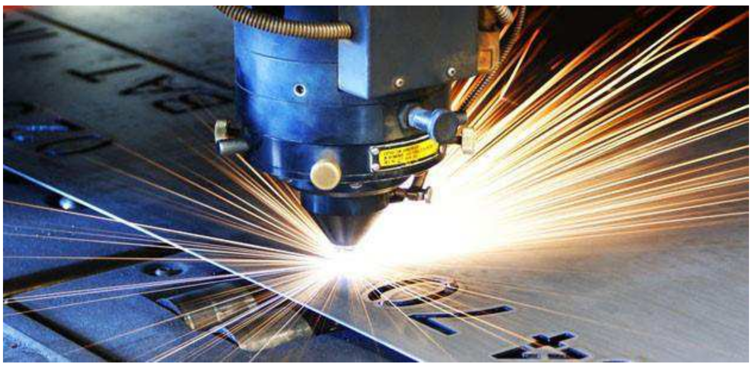
Application note for laser processing using EL-10-42-OF tunable lens and EL-E-OF-A driver board



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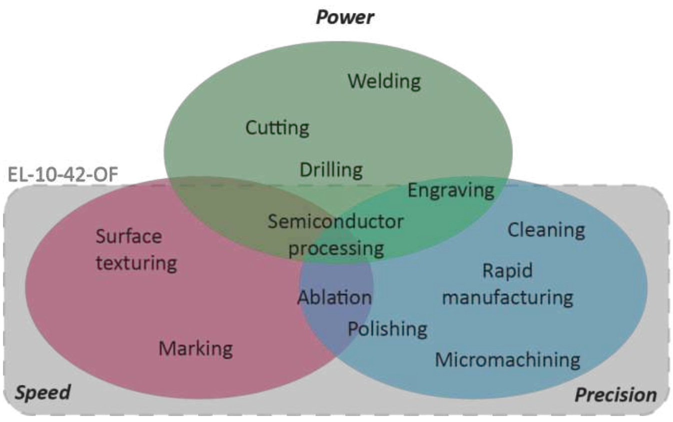
1. Introduction

Nowadays, the common solution available on the market for controlling the z-coordinate in laser processing is using the mechanical translation. However the major limitations of this approach are the slow speed and a small range in z-travel. The delicate movable parts are limited in their lifetime, require lots of space to be integrated in an existing system and often need to be water cooled.

In this Application Note, we will describe how to integrate the Optotune EL-10-42-OF tunable lens, driven with EL-E-OF-A electronics board, into a laser marking system. We will provide general guidelines of using an EL-10-42-OF lens as well as present a compact setup for a laser marking system. The EL-10-42-OF lens is light, compact and has a fast response time as well as long lifetime. Therefore, it would be an ideal candidate to overcome many of the downsides of a mechanical solution while at the same time ensuring reduced costs.

The EL-10-42-OF lens is designed for pulsed lasers of near-infrared wavelength between 950 nm and 1100 nm. This opens the possibility of using the EL-10-42-OF lens for various laser processing applications.



Advantages using EL-10-42-OF:
> Large scan volume
> High speed for true 3D marking
> High reliability

2. Controlling EL-10-42-OF lens with EL-E-OF-A driver board

Optotune EL-E-OF-A driver board is designed to control EL-10-42-OF lenses. While the EL-10-42-OF lens shifts the laser spot in z- (vertical) direction, the galvo mirrors deflect the laser spot in the x-y- (horizontal) plane. This approach is implemented in the compact laser marker presented in Section 3 and schematically shown on the left panel of Figure 1.

The communication between the PC (the user) and the XY2-100 digital controller card is often established via a serial bus, e.g. USB. Within the extended XY2-100 protocol, the z-axis used to control EL-10-42-OF lens is already available, in addition to the x- and y-axes that control the galvo mirrors. The controller card transmits the digital signal for the x- and y-axis to the scan head for controlling the galvo mirrors. The digital signal of the z-axis has to be converted via a digital-to-analog board (e.g. SCAPS AEB-2 board) into an analog voltage. The right panel of Figure 1 shows another possible integration, in case the XY2-100 controller card has an auxiliary analog voltage output. This voltage output is often used to control an external device such as a z-stage.

Both situations do not allow for fast 3D laser processing since every time the z-coordinate is changed, the machining process is interrupted. However, for many applications where plane objects at different heights are laser marked (for z-stepping), this is a feasible solution. Only when the driver board for the z axis is synchronized with an industrial real-time bus, e.g. the XY2-100 protocol, the key benefit of high focusing speed can be fully exploited and achieve laser control following a curved contour.

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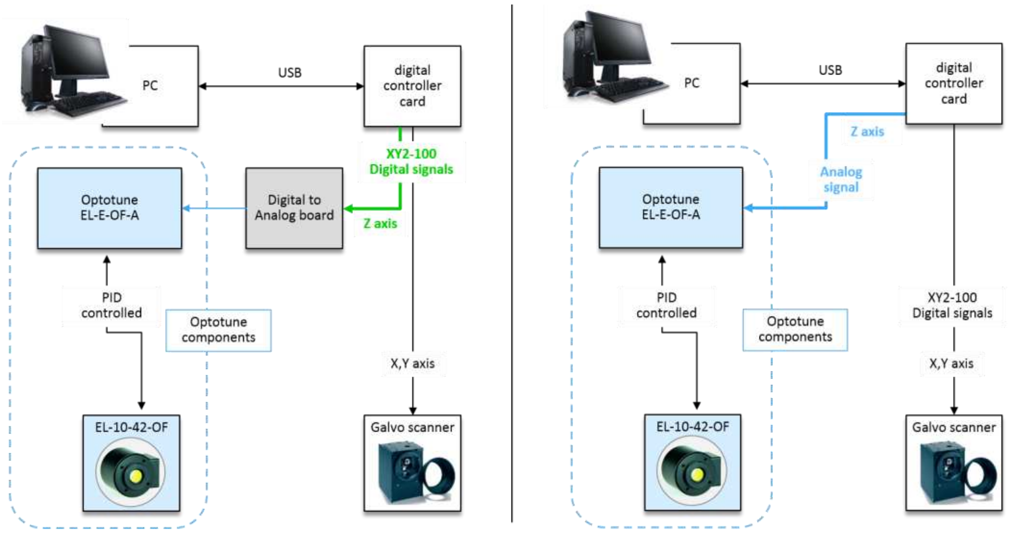

Figure 1: The left panel shows the integration of Optotune EL-10-42-OF within a digital protocol that provides x,y and z-signals. The signal of the z-axis is converted into an analog signal for using Optotune EL-E-OF-A board. On the right, the lens is directly controlled by the analog signal provided by the controller card.

3. Integration of the system

Figure 2 shows an integration example of a compact laser marking system built at Optotune. The EL-10-42-OF is small such that it can just be mounted in the empty space between the laser output and the galvo head (see Figure 3). The mechanical holder for the EL-10-42-OF lens is required and should make sure that the laser beam, the EL-10-42-OF lens and the aperture of the galvo head are coaxial.

Figure 2: Laser marking system using Optotune's electrically focus tunable lens EL-10-42-OF for fast z-axis focusing.

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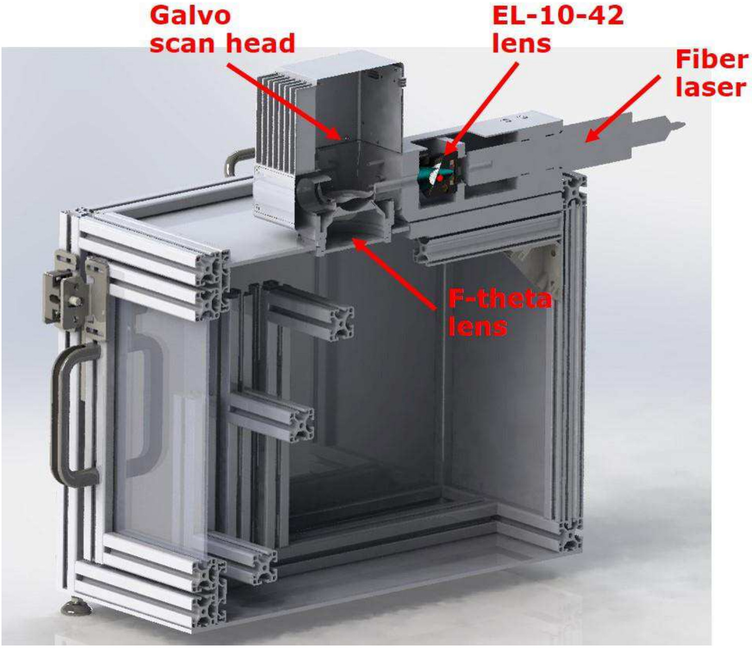

Figure 3: Schematics of Optotune laser marking demo setup. Optotune electrically focus tunable lens EL-10-42-OF is placed between laser head and galvo mirrors, indicated by the arrow.

The following table summarizes the main specifications of the demo marking system.

Basic Specifications

Outer measures	400 x 400 x 300	mm
Weight	approximately 15	kg
Marking field at central position	100 x 100	mm
Laser class	1 (with housing)	
Laser vendor	IPG / Nufern	
Maximal laser power	20 / 50	W
Laser wavelength	1064	nm
Typical spot size	approximately 70	µm
Beam quality M^2 (IPG specs)	< 2	
Focal length f-theta lens	160	mm
Typ. Jump speed	6000	mm/s
Z-tuning range	100	mm
Software	SCAPS SAMLight	

3.1. Standard integration: with f-theta lens

In addition to the standard integration example shown in the previous section, we summarize various optical layouts in combination with the EL-10-42-OF lens depending on different applications. In Figure 4 the resulting z-tuning range in combination with different f-theta lenses is shown[1].

The output laser beam has a diameter of about 6 mm. The EL-10-42-OF lens is placed on the beam path from the laser output to the galvo scanner. The beam is then reflected by the galvo mirrors that allow beam deflection along x- and y-direction on the target. The field size shown in the simulation results from the mirror deflection

[1] Upon request, we provide ZEMAX models of the shown configurations.

angle of +/- 10°. The z-position of the laser spot is controlled by tuning the focal length of EL-10-42-OF lens. For the f-theta lens with a longer focal length, the resulting z-tuning range as well as the marking field size increases. In each configuration, the focal length of the EL-10-42-OF is tuned over the maximal range (from -2 diopter to +2 diopter). Field flattening and final focusing onto the marking plane are done by the f-theta lens. This configuration is simple to implement since the EL-10-42-OF is directly integrated in the existing system.

Note: There are remaining field distortions due to imperfections of the f-theta optics. Those effects are slightly enhanced when operating the f-theta lens with the EL-10-42-OF because of the introduced convergence or divergence of the input beam that enters the f-theta lens. For best marking quality, this has to be taken into account on the software side by e.g. introducing a correction grid.

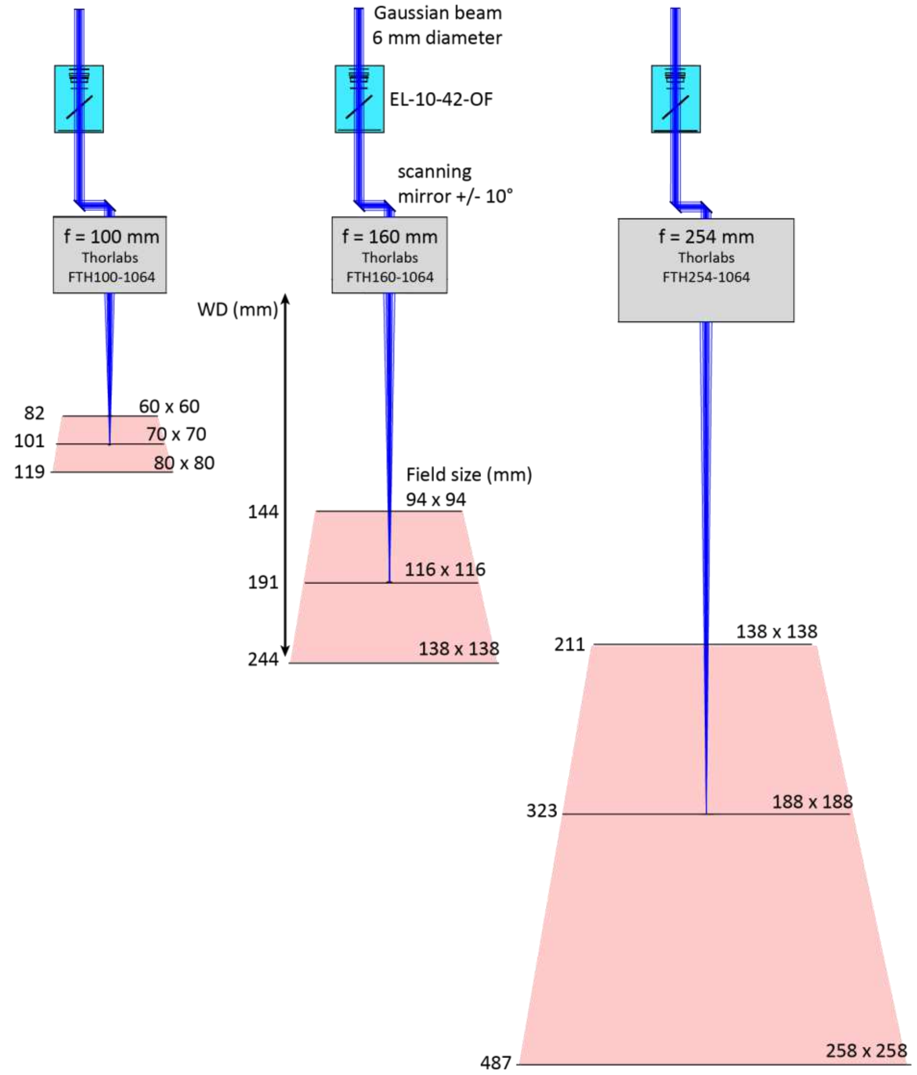

Figure 4: Laser scanning system with the EL-10-42-OF, galvo scanning mirror and different f-theta lenses f = 100, 160 and 254 mm. The corresponding z-scanning range and change of working distance (WD) is indicated by the black arrow. The red color indicates the marking volume for the different situations.

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3.2. Combination with a galilean telescope

The configurations described in Section 3.1 offer a certain degree of freedom regarding the size of working area, z-tuning range and spot size. However, for many applications more flexibility is desirable in order to optimize the tuning range and spot size. The first possibility would be to use the EL-10-42-OF lens in combination with a Galilean telescope (beam expander), which introduces the beam magnification factor as an additional degree of freedom. The generic design is shown in Figure 5. The EL-10-42-OF is placed between the two fix-focus lenses that constitute the beam expander. The beam is then sent onto the galvo mirrors and is focused by the f-theta lens.

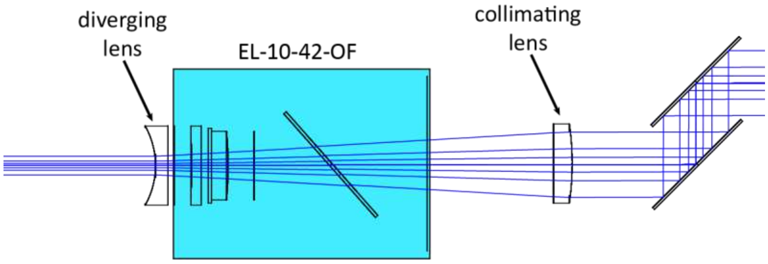
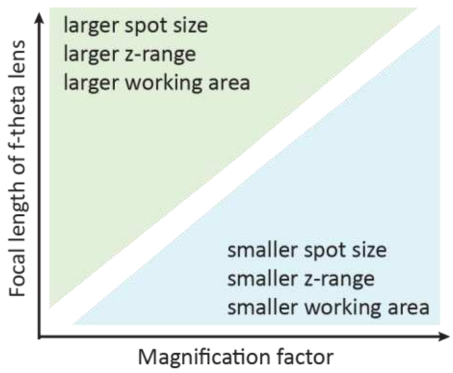


Figure 5: Generic design of a Galilean telescope combined with the EL-10-42-OF. The beam magnification factor is a crucial parameter to optimize tuning range and laser spot size.

We summarize the scaling of the four most important parameters below presented as bullet points. The graph on the left shows the qualitative behavior. According to customer's requests, we are able to provide optical design for the system integration.



- Working area
- Z-axis tuning range
- Laser spot size
- Change of spot size over the tuning range

3.3. Combination with off-the-shelf beam expanders

As discussed in Section 3.2 the spot size and tuning range along the z-axis can be adjusted in combination with a beam expander. A reasonable range of spot sizes and z-ranges are possible by using an off-the-shelf beam expanders. The generic optical setup is illustrated in Figure 6. The beam expander has to be placed as close as possible after the EL-10-42-OF, however the precise distance is not a very crucial parameter. In order to avoid beam clipping on the galvo mirrors, the mirror size has to be large enough compared to the laser beam size after magnified.

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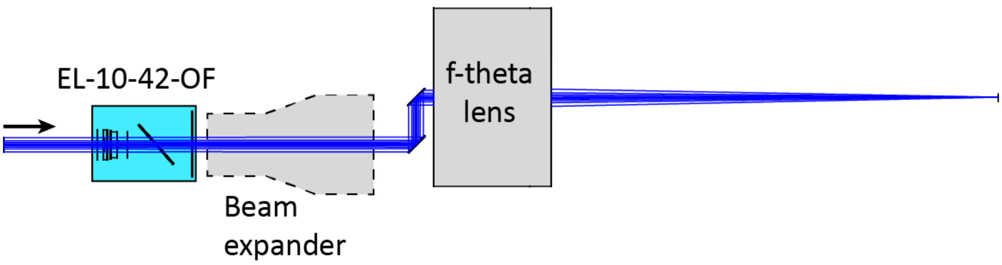

Figure 6: Optical setup to integrate an off-the-shelf beam expander. The beam expander has to be placed directly after the EL-10-42-OF.

We also investigate the properties of an optical system using different beam expanders and f-theta lenses. Assuming the output laser beam size is 8 mm, the z-range and the focused spot sizes achieved in combination with the EL-10-42-OF lens are summarized in the following table. We verified components from different vendors showing that the results shown in the table negligibly differ by only a few percent.

		**1x (no expander)**	**1.5x**	**2x**	**3x**
100	**Max. input beam size (mm)**	8	8	6	4
	z-range (mm)	39	18	10	4
	Spot size (um)	26	17	18	17
160	**Max. input beam size (mm)**	8	8	6	4
	z-range (mm)	103	46	26	11
	Spot size (um)	42	28	28	27
254	**Max. input beam size (mm)**	8	8	8	6
	z-range (mm)	263	117	65	27
	Spot size (um)	70	46	35	28

4. Calibration of the z-axis

Controlling the lens via the EL-E-OF-A driver board requires an analog voltage ranging from 0 to 5V. The resolution of the signal should be at least 12 bit. The EL-E-OF-A controls the optical power of the lens and hence allows for shifting the laser spot in z-direction, illustrated on the left panel of Figure 7. It is necessary to perform a calibration between the control voltage and the laser spot position in z direction due to production tolerances of the lens. Detailed z-axis calibration procedure using SAMLight is shown in Appendix 1.

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After calibration, the set signal directly represents the tuning range in z-direction between z_{min} and z_{max}, as shown on the right panel of Figure 7. The actual z-tuning range depends on the optical layout in which the EL-10-42-OF is integrated. The calibration should be done once and the data can be stored via a lookup table in the marking software. It is recommended to create at least ten calibration points. More points will increase the precision of the z-axis control.

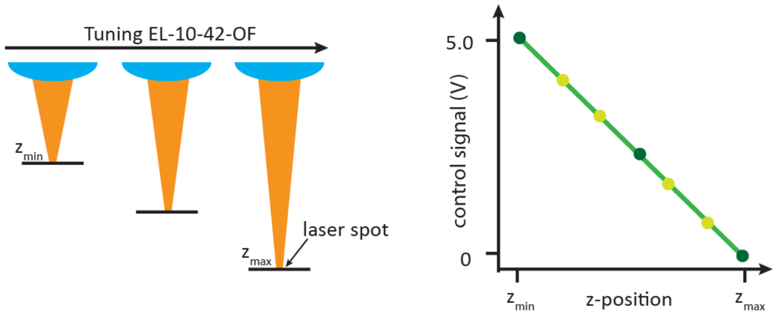

Figure 7: The left panel shows how the z-position of the laser spot is changed by tuning EL-10-42-OF. The right panel illustrates the calibration curve of control signal (0-5 V) versus the focal positions in z axis. The light green points represent further points required to increase the precision of the calibration.

5. Marking tests

Using the Optotune's demonstration marking machine (see Figure 2), a 10 x 10 mm rectangle is marked at the two extreme positions of the marking volume. Examining the result under a microscope with 8x magnification, no significant difference or degradation is visible.

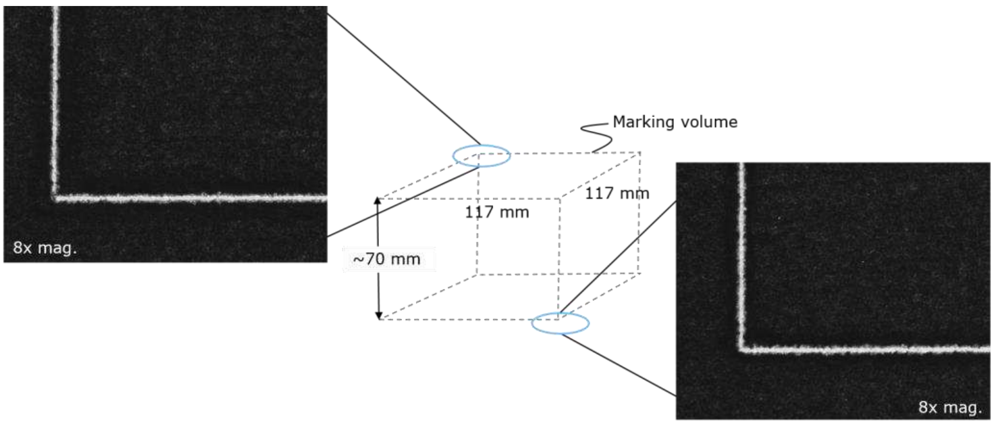

Figure 8: Marking quality at two extreme positions of the marking volume. In both cases, a small 10 x 10 mm rectangle is marked and the result is examined with an 8x microscope. No significant difference is visible.

In a second test, we investigate the influence of the EL-10-42-OF on the marking quality. A dot matrix of 4 x 4 points is marked on a horizontal plane. The left image of Figure 9 shows the result when the EL-10-42-OF is in the beam path and the right image presents the situation when the EL-10-42-OF is taken out of the system. The marked samples are investigated with an 8x microscope. As a result, there is no visible degradation induced by the EL-10-42-OF.

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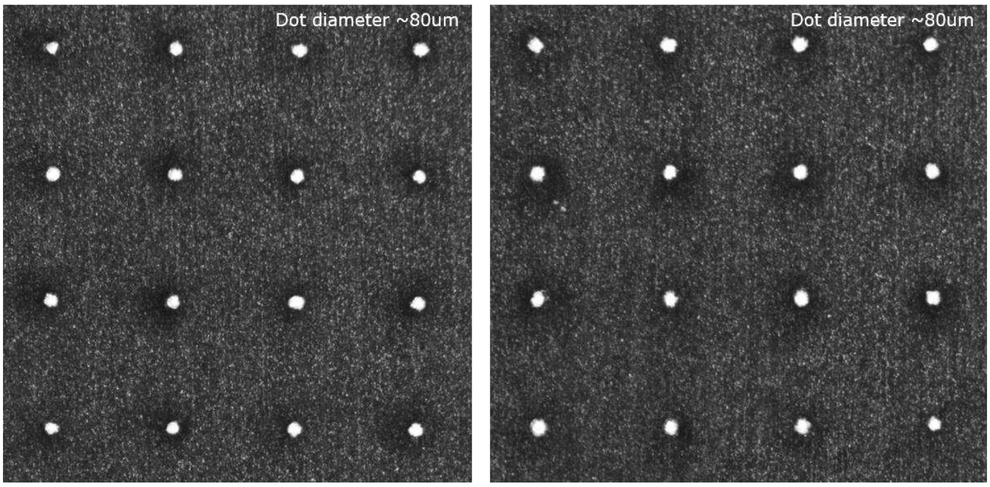
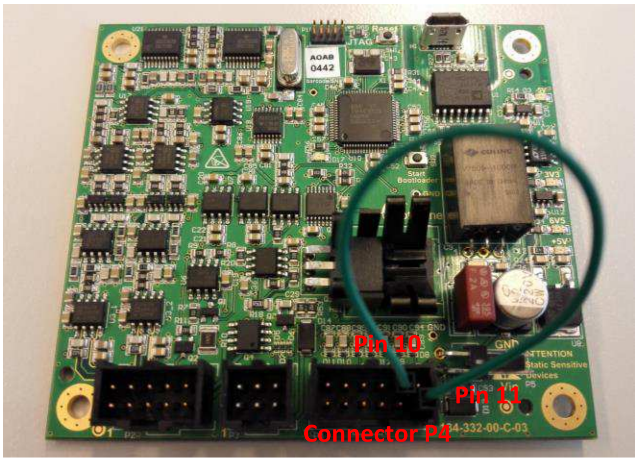


Figure 9: Comparison of marking quality with and without the EL-10-42-OF in the beam path. Under the microscope (8x mag.), no difference between the two situations.

Note: The EL-E-OF-A electronics is especially developed to control the EL-10-42-OF lens. In laser processing applications, pulsed and high-power laser beams are used, posing considerable challenges on the precision of the optical feedback (OF) control. Tiny amounts of stray light still introduce an offset on the OF, shifting the actual set value. Although the remaining shift is canceled electronically, implemented on the EL-E-OF-A board, for efficient OF control laser repetition rates >= 20 kHz are recommended.

6. Linearization: Focal power v.s. analog voltage

In the firmware of the EL-E-OF-A driver board, we have implemented a feature linearizing the focal powers of the lens with the applied voltages. By actively pulling Pin 11 in Connector P4 low, the user enables this linearization feature. A simple way to do it is by connecting Pin 11 and Pin 10 (ground) as shown in the picture below.



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The measurement results with and without the linearization enabled are presented in Figure 10.

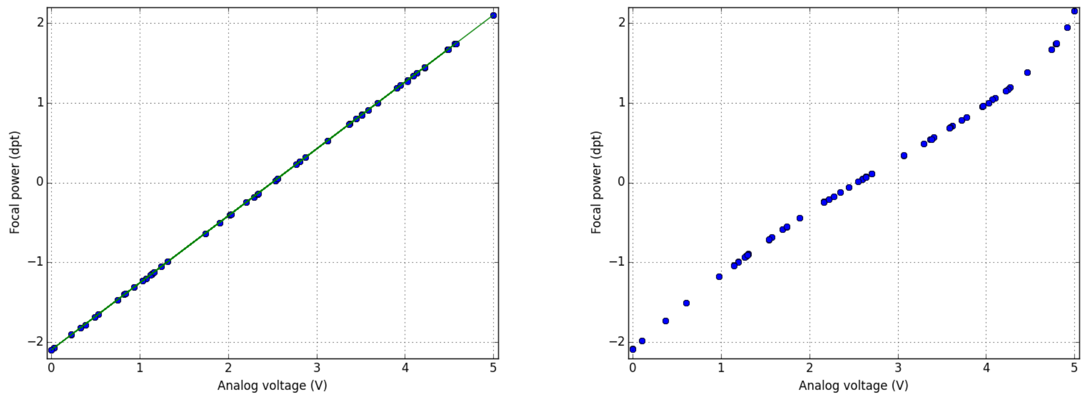


Figure 10: The measurement of focal powers (dpt) versus applied voltages. The linearization feature is enabled on the left and disabled (by default) on the right.

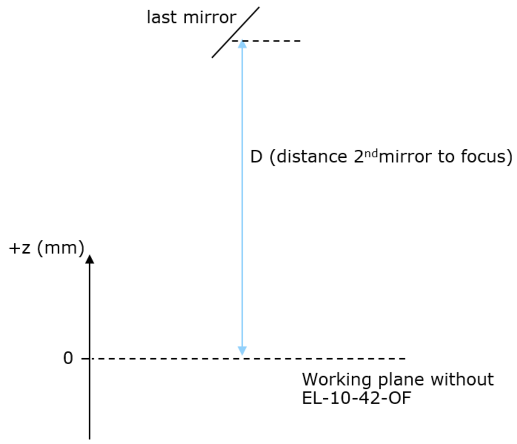
The main advantage of this feature is that when more than two marking systems need to be calibrated in the factory, the whole z-axis calibration processes can be simplified. The first marking system is considered as the master system. This one has to go through the full z-axis calibration described in Section 4 for which more than ten data points are recommended to take. If the linearization feature is enabled, in theory the calibration procedure can be simplified using two calibration points only for the rest of machines. However, a look-up table containing more than ten data points is still needed in order to achieve optimal and precise control for the z-position. Upon request, Optotune provides an EXCEL sheet for the user to generate a new look-up table from the two-point calibration result based on the data taken from the master system.

7. Further information & support

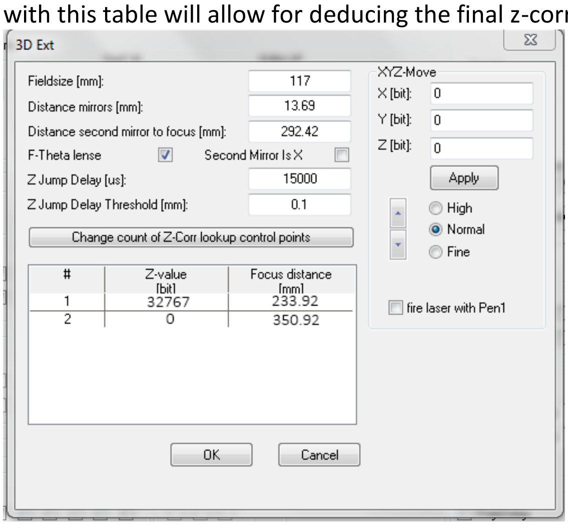
Our application engineers are happy to help you with the integration of our products in your design. Don't hesitate to contact us at sales@optotune.com or to call us at +41 58 856 3000.

Appendix 1: How to perform z-calibration with EL-10-42-OF in SAMLight

The following procedure describes one possible way to calibrate the z-position of the marking laser spot against the control voltage. The method has been successfully tested in a standard marking system described in this application note. The obtained precision is 500 um. For higher precision, a beam profile measurement is recommended. The marking software SAMLight (SCAPS) allows for easy integration of the z-calibration via a look-up table. The coordinate system is defined as:



1. It is assumed that the distance D from second mirror to the working plane is already known (in the exemplary system, D = 292.42 mm). Before integrating the EL-10-42-OF, this has to be measured precisely, e.g. with the help of a mechanical z-stage.
2. As a first step, a temporary z-correction look-up table has to be created. The measurements done with this table will allow for deducing the final z-correction table.



The table is defined only by the two DAC end points DAC_1 = 32767 and DAC_2 = 0, which correspond to 0 and 5V respectively. This is the maximum allowed range of the lens' control voltage. The corresponding distances (mm) are calculated as seen in the table below:

DAC_1	32767	D – (x,y-working area / 2) = D_1
DAC_2	0	D + (x,y-working area / 2) = D_2

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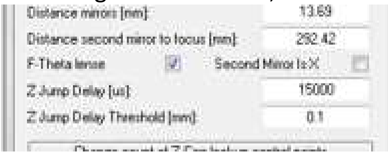
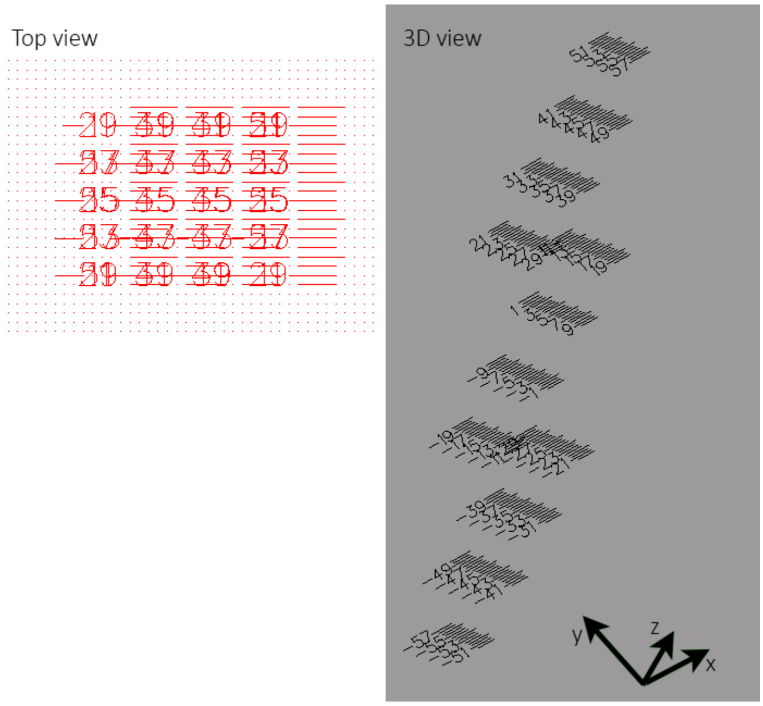
3. When using an f-theta lens, the corresponding check box in SAMLight has to be enabled.



4. Load the pre-defined marking job file "Find_DAC_Values.sjf" in SAMLight.



This job file serves as a vertical "ruler". It consists of lines ranging from -57…+57 mm in z-direction. The lines have 0.5 mm spacing. If your x,y-working area is smaller than this range, you have to delete a few lines in the job file such that the z-range < x,y-working area. Otherwise the error message "Galvo out of range" will appear when clicking "start mark".

5. Next, define the number of **z-values of the final z-correction** table in a separate spread sheet. The points have to be within the maximum physical z-tuning range (e.g. -45…+45 mm). For example:

z-value (mm)
-38.7
-17.5
0
29.8
42.6

6. Position a marking sample (e.g. anodized aluminum plate) at the first point of the final z-correction table (e.g. 39.82 mm in this example). According to the definition of the coordinate system, a negative z-value (mm) means below the zero plane and a positive value above the zero plane. This is consistent with the definition of the coordinate system in SAMLight. Start marking the job file.
7. Change the z-position of the marking sample to the next point of the final z-correction table and mark the job file again. Repeat this procedure for all z-values.
8. Extract the marked z-position values F_z from the marking sample. To do so it is helpful to analyze the samples under a standard microscope (e.g. 8x magnification). This increases the precision when locating the "best" line that was in focus.

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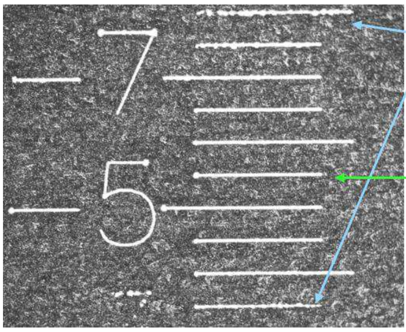

9. After this analysis, your z-correction table might look like shown below. At z-value = 0 mm, the marked value on the sample is not necessarily zero due to a possible offset. The calibration will take this offset automatically into account.

z-value (mm)	F_z (marked value on sample)
-38.7	-34
-17.5	-17.5
0	-1
29.8	34
42.6	48.5

10. Next, calculate the distances $D_z = D - F_z$ with D = 292.42 mm in this example. As a next step, in order to establish the linear relation between the DAC values and the values D_z we have to calculate

$$DAC_z = a \cdot D_z + b$$

with the coefficients (from step 2.)

$$a = \frac{DAC_2 - DAC_1}{D_2 - D_1}, \quad b = \frac{D_2 \cdot DAC_1 - D_1 \cdot DAC_2}{D_2 - D_1}.$$

Now, the table looks like below

z-value (mm)	F_z (marked value on sample)	D_z	DAC_z
-38.7	-34	326.42	6861
-17.5	-17.5	309.92	11482
0	-1	293.42	16103
29.8	34	258.42	25906
42.6	48.5	243.92	29966

11. As a final step, one has to calculate D – (z-value). D is the distance from 2nd mirror to working area. The final look-up table implemented in SAMLight, highlighted in red, looks like:

z-value (mm)	F_z (marked value on sample)	D_z	DAC_z	z-value absolute (mm)
-38.7	-34	326.42	6861	331.12
-17.5	-17.5	309.92	11482	309.92
0	-1	293.42	16103	292.42
29.8	34	258.42	25906	262.62
42.6	48.5	243.92	29966	249.82

The two red columns are used in SAMLight as the final z-calibration look-up table. Note that in SAMLight, the "Focus distance (mm)" has to be entered in ascending order:

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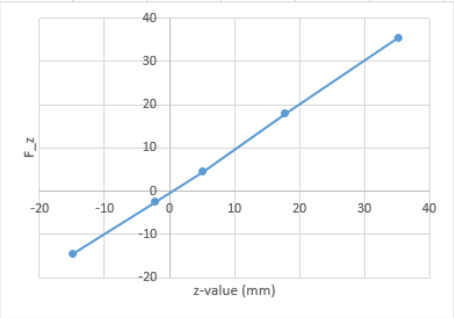
Z-value (bit)	Focus distance (mm)
29966	249.82
25906	262.62
16103	292.42
11482	309.92
6861	331.12

12. *Optional:* one can perform a verification measurement. If the calibration is correct, one obtains the same values when repeating steps 5 to 8. The exemplary measurement shown below confirms this relation. The deviations are small and within the precision of the method described in step 8.

z-value (mm)	F_z
-14.93	-14.5
-2.21	-2.5
5.1	4.5
17.81	18
35.3	35.5



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Appendix 2: Response time and oscillation speed

Using the EL-E-OF-A electronics to control the EL-10-42-OF, we characterize 3 different situations (step, sinusoidal and triangular signal) that cover most of the "generic" trajectories required in z-stepping laser processing. The results reflect the combined effects of finite bandwidth of the control electronics (dominating part) and the physical limit of the lens itself.

Step response

The step response of the optical feedback signal itself is measured in order to quantify the speed of focus change. The control voltage at the input of the EL-E-OF-A is modulated with a rectangular shape at a frequency of 10 Hz. In Figure 12 the blue data show the lower and upper value of the control voltage with 0.5 V and 4.5 V respectively, corresponding to a 10%-90% step. The response of the optical feedback signal is shown in the red data, jumping from -1.6 to +1.6 dpt. In both rising and falling curves, it takes 12 ms to reach the set value within 5% deviation. The small, step-like features of the feedback signal originate from the signal sampling of 1.1 kHz. The data are acquired with an oscilloscope.

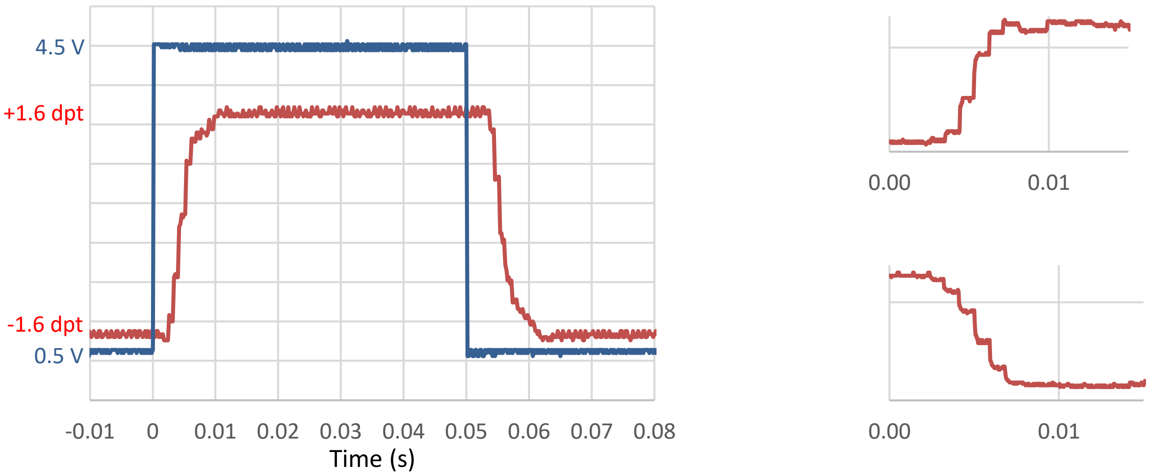

Figure 11: EL-10-42-OF step response of the optical feedback signal (red). The blue data shows the applied voltage step at the input of the EL-E-OF-A control board. The small figures on the left show a zoom on the rising and falling edge.

In a more detailed analysis we investigate the scaling of the response time for different step heights. The results are depicted in Figure 12, showing that in general, the total response time decreases with smaller step height. There are two contributions to the total response time. A constant delay of 3.5 ms (dashed line) which originates from the finite sampling rate of the EL-E-OF-A. And the finite time (finite number of steps) that is required to reach the new set point, typically 6 to 7 steps (blue solid line).

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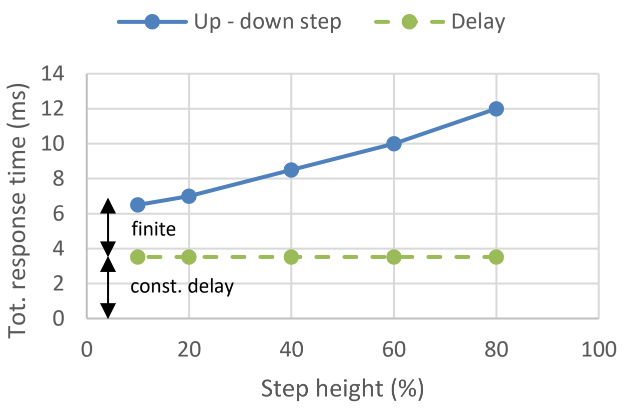
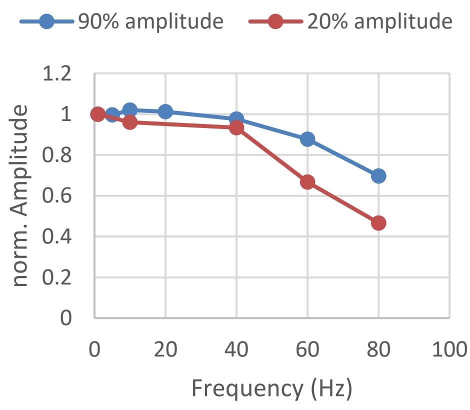


Figure 12: Total response time versus step height. The total response time consists of two contributions, a constant delay and a finite rise time which decreases for smaller step height.

Sinusodial modulation

We apply a sinusoidal set voltage with a function generator and observe the amplitude and phase delay of the optical feedback signal. On the left of Figure 13, the amplitude normalized to the DC limit (constant set voltage) is shown. The amplitude starts to decrease above 40 Hz. The main reason is that there is a constant delay of 5.5 ms, reflected in a linear increase of the relative phase (in degree), shown in the right of Figure 13. When comparing 90% modulation amplitude and 20% amplitude, no significant difference is visible.



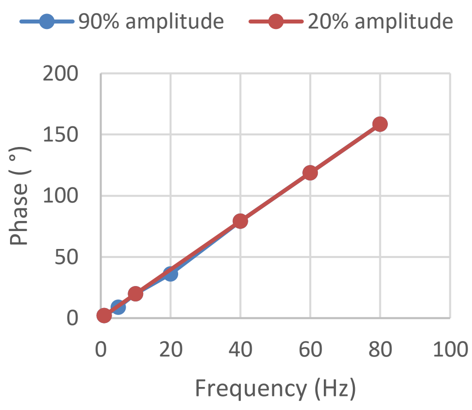


Figure 13: On the left, the normalized amplitude versus frequency is shown. At 40 Hz, the amplitude starts to decrease. Within the measurement precision, the results are equal for the 90% and 20% amplitude. The right side shows the linear increase of relative phase, reflecting a constant delay.

Triangular modulation

A triangular modulation resembles the processing of inclined planes. Increasing the modulation frequency corresponds to either a steeper plane or increased processing speed. Such a profile is very challenging since even a small delay time leads to a "rounded edge" of the start and end points of the ramps. Consequently, the frequency at which the amplitude starts to decrease is lower than the case of applying sinusoidal modulation. At a frequency of 20 Hz, the amplitude is 90% of the DC limit. Regarding the phase shift, the behavior is very similar to the case of sinusoidal modulation and we observe a constant delay of 5.5 ms.

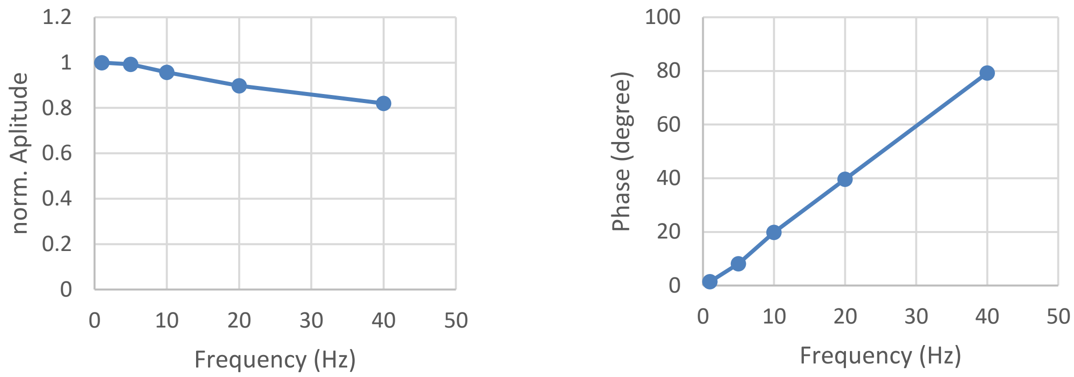


Figure 14: The left side shows the normalized amplitude versus frequency. At 20 Hz, the amplitude is 90% of the DC limit. The linear increase in relative phase, shown on the right side, is characteristic for a constant delay time.

Conclusions

In such a setup, fast 3D laser processing is quite challenging regarding the synchronization of z- and x,y- axis. The main technical limitation is that the dynamics of the EL-10-42-OF[2] (z-axis) is different from the galvo mirrors (x,y-axis). Most importantly, different delay times, or “acceleration times”, have to be considered by having independent control over z- and x,y- axis at the software end. Higher bandwidth of the control electronics will allow for reaching the physical limit of the lens, which has a resonance frequency of 200 Hz. This indicates that a higher operation speed should be feasible. For details, please refer to the other Optotune application note for fast laser processing.

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[2] See also datasheet of EL-10-42-OF