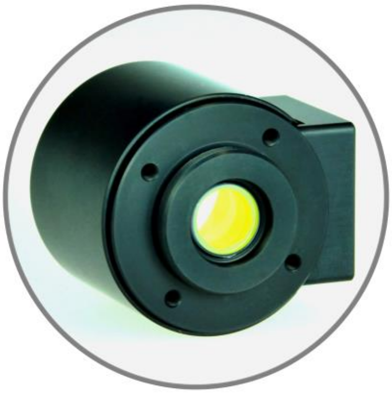
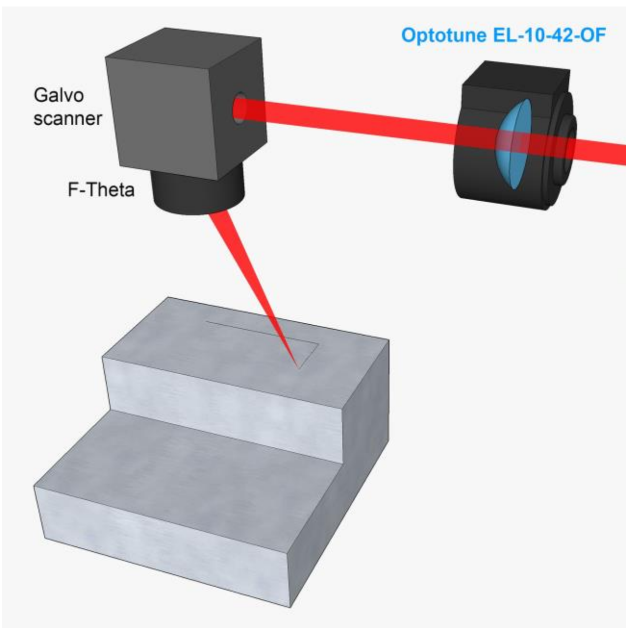


Application note for laser processing

using EL-10-42-OF tunable lens and EL-E-OF-A controller board



Optotune Switzerland AG | Bernstrasse 388 | CH-8953 Dietikon | Switzerland
Phone +41 58 856 30 00 | www.optotune.com | info@optotune.com

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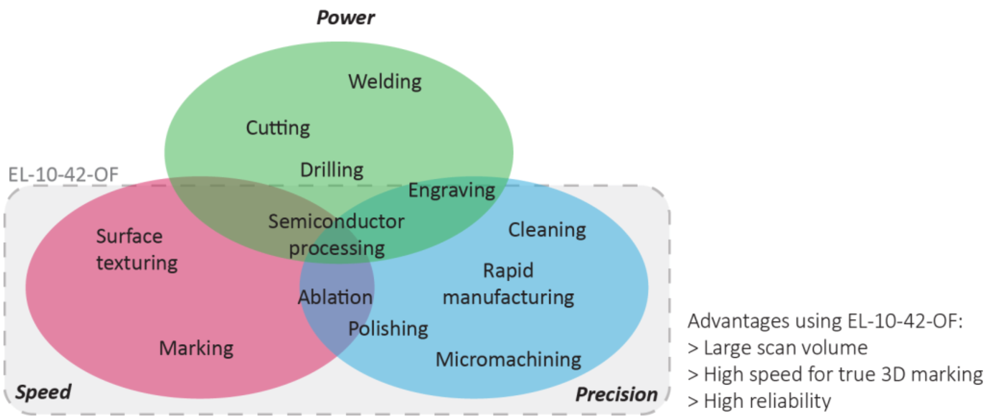
1. Introduction

Nowadays, the common solution available on the market for controlling the z-coordinate in laser processing is based on mechanical translation of optics. The major limitations of this approach are slow speed and a small range in z-travel. In addition, the delicate movable parts are limited in their lifetime and require a lot of space for system integration

In this Application Note, we describe how to integrate the Optotune EL-10-42-OF tunable lens, driven with EL-E-OF-A electronics board, into different laser processing systems. 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, designed for pulsed lasers, comes in two wavelength options: the near infrared between 950nm and 1100nm, and the visible at 532nm. This opens the possibility of using the EL-10-42-OF lens for various laser processing applications, as illustrated below.



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

Optotune's EL-E-OF-A controller 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 a 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.

Configurations with EL-E-OF-A are well suited for all applications where plane objects need to be laser processed at different heights (z-stepping). Since the machining process is interrupted every time the z-coordinate is changed, fast 3D processing is better established using the digital controller, as explained in a separate application note. In this configuration the controller board for the z axis is synchronized with an industrial real-time bus, e.g. the XY2-100 protocol, allowing for high focusing speed along a 3D contour.

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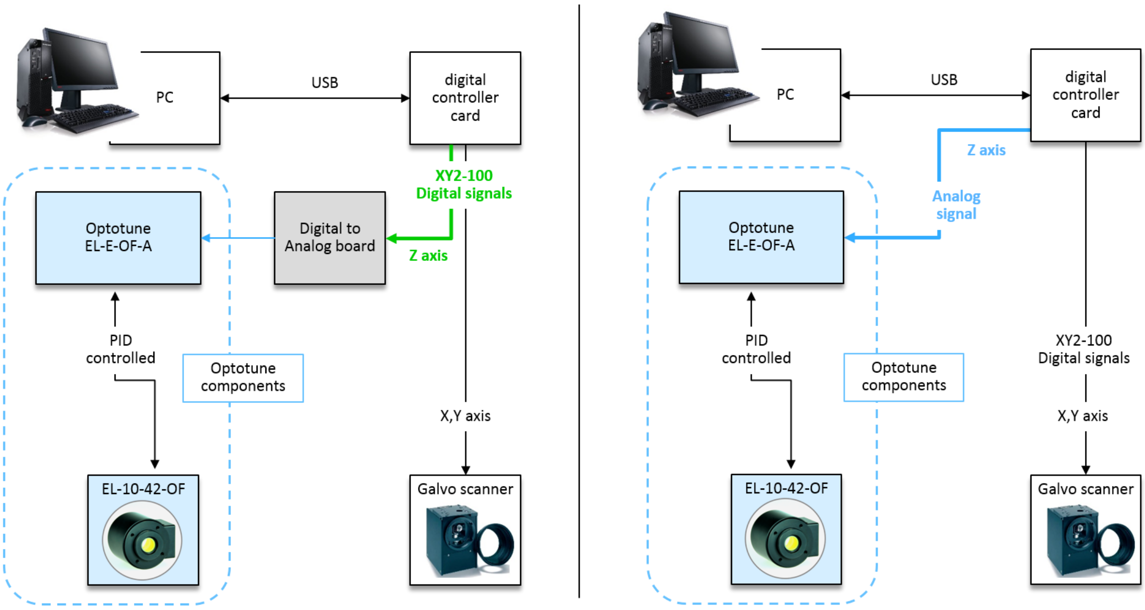

Figure 1: The left panel shows the integration of Optotune EL-10-42-OF within a digital protocol that provides x,y and z-signals. The signal of the z-axis is converted into an analog signal for using Optotune EL-E-OF-A board. On the right, the lens is directly controlled by the analog signal provided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

3. Integration of the system

Figure 2 shows an integration example of a compact 2.5D laser marking system at 1064 nm built at Optotune. Being compact, the EL-10-42-OF can be easily mounted in the empty space between the laser output and the galvo head (see Figure 3). A specially designed mechanical holder for the EL-10-42-OF lens is required to make sure 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 and the analog controller EL-E-OF-A for fast z-axis focusing.

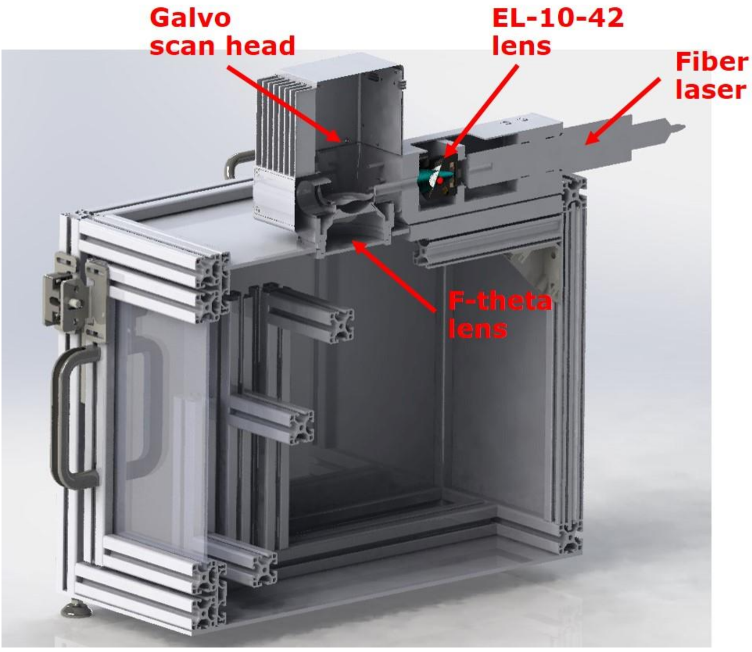

Figure 3: Schematics of Optotune laser marking demo setup. Optotune electrically focus tunable lens EL-10-42-OF is placed between laser head and galvo mirrors.

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 60	µm
Focal length f-theta lens	160	mm
Typ. Jump speed	6000	mm/s
Z-tuning range	100	mm
Software	SCAPS SAMLight	

3.1. Integration with f-theta lens

The setup shown in previous section is one of several typical layouts employed by laser processing systems. In this section we show three common optical layouts in combination with the EL-10-42-OF lens. The resulting z-tuning range in combination with different f-theta lenses is shown[1] in Figure 4.

In all three cases 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 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

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

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(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: Field distortions caused by imperfections of the f-theta optics 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 should be taken into account on the software side by, for instance, introducing a correction grid.

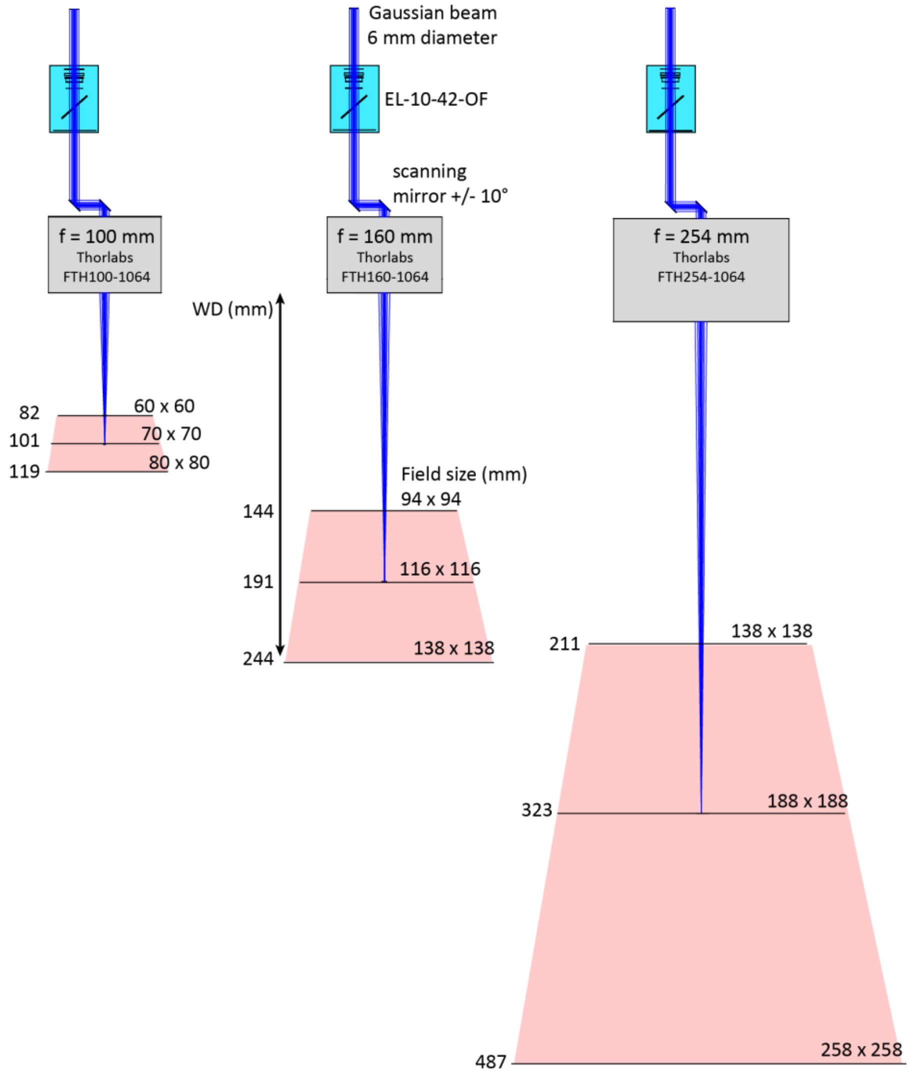

Figure 4: Laser scanning systems with the EL-10-42-OF, galvo scanning mirror and f-theta lenses. Different f-theta focal lengths (f = 100, 160 and 254 mm) result in different z-scanning range, the working distance (WD), and the marking volume (indicated in red)..

3.2. Integration 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 to optimize the tuning range and the spot size. One possibility is 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.

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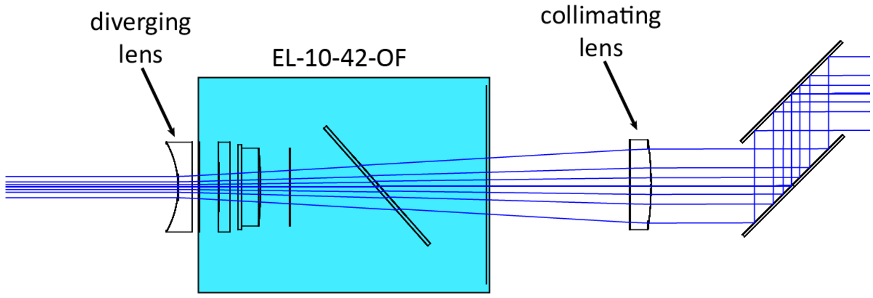
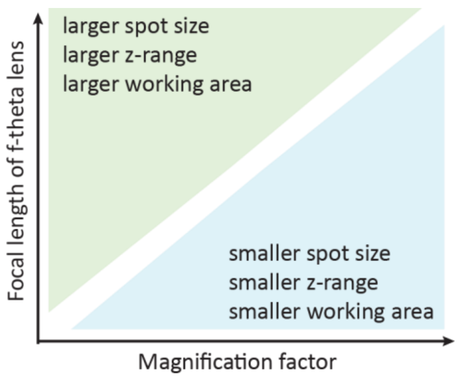


Figure 5: Generic design of a Galilean telescope combined with the EL-10-42-OF. The beam magnification factor is a crucial parameter to optimize tuning range and laser spot size.

The graph below depicts qualitatively how the working area, the z-axis tuning range and the laser spot size can be controlled by different combinations of f-theta lenses and Galilean magnification optics. According to customer's requests, we can advise about the optical design for the system integration.



- Working area
- Z-axis tuning range
- Laser spot size

3.3. Integration with off-the-shelf beam expanders

A range of spot sizes and z-ranges is also feasible with off-the-shelf beam expanders. A generic optical setup is illustrated in Figure 6. The beam expander should be placed as close as possible after the EL-10-42-OF, however, a precise positioning is not so crucial. To avoid beam clipping on the galvo mirrors, the mirror size must be large enough to accommodate the laser beam after magnification.

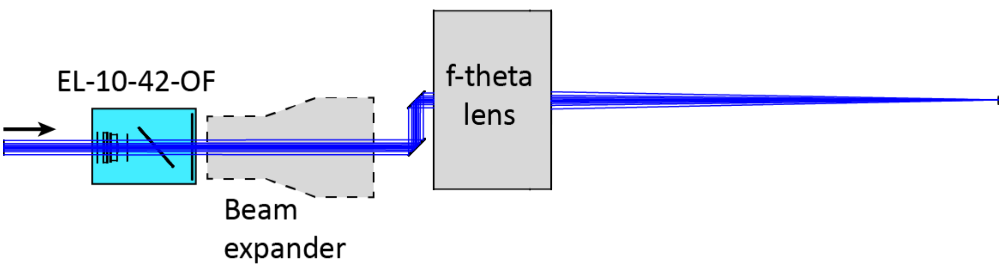


Figure 6: Optical setup to integrate an off-the-shelf beam expander, which must be placed directly after the EL-10-42-OF.

Assuming the output laser beam diameter of 8 mm, the z-range and the focus spot size as summarized in the table below can be obtained with various beam expanders combined with the EL-10-42 lens. Beam expanders from different vendors have been tested, showing a negligible deviation in performance of only a few percent.

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		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 controller 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, as 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.

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.

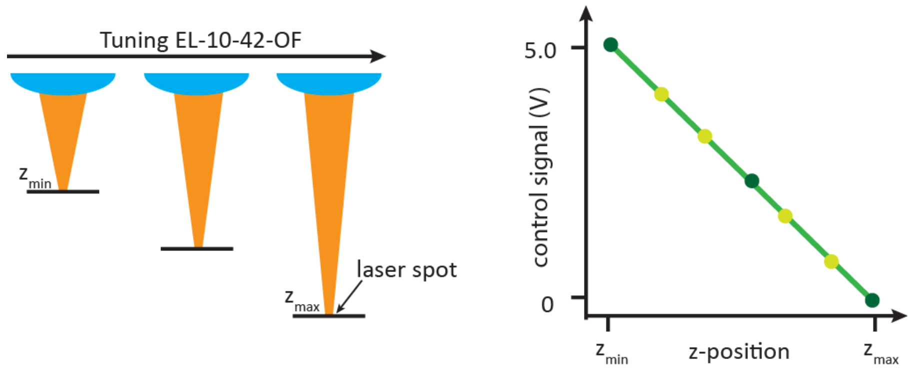

Figure 7: The left panel shows how the z-position of the laser spot is changed by tuning EL-10-42-OF. The right panel illustrates the calibration curve of control signal (0-5 V) versus the focal positions in z axis. The light green points represent further points required to increase the precision of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

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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.

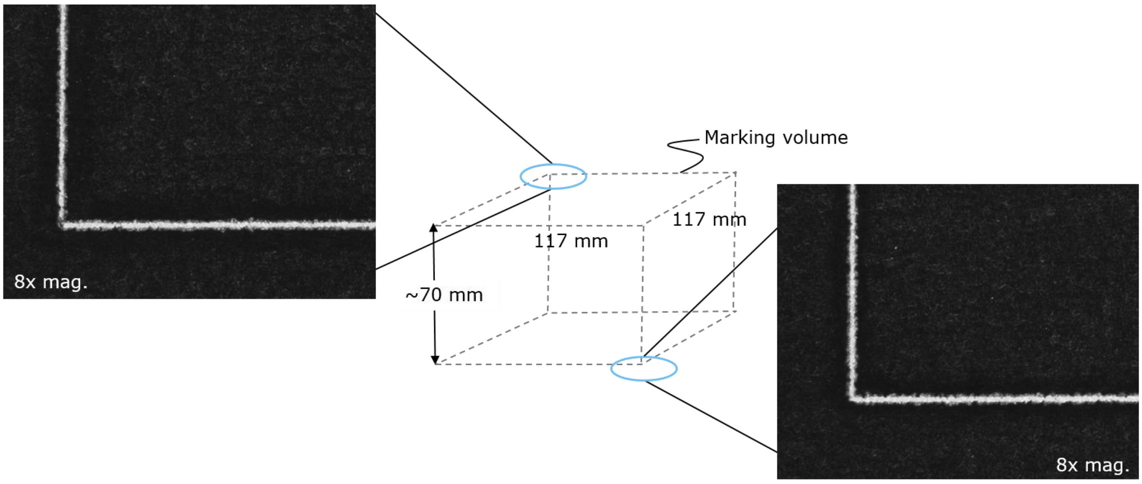

Figure 8: Marking quality at two extreme positions of the marking volume. In both cases, a small 10 x 10 mm rectangle is marked and the result is examined with an 8x microscope. No significant difference is visible.

In a second test, we investigate how the insertion of the EL-10-42-OF affects 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, whereas the right image shows the marking results when the EL-10-42-OF is taken out of the system. The marked samples, investigated with an 8x microscope, indicate no visible degradation in image quality due to the presence of the EL-10-42-OF.

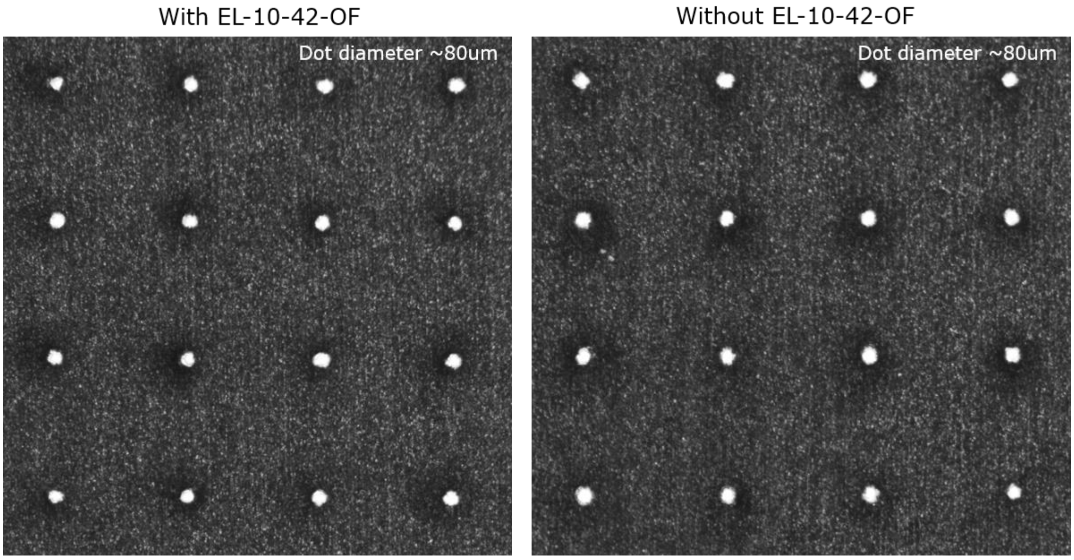

Figure 9: Comparison of marking quality with and without the EL-10-42-OF in the beam path does not show any difference between the two setups.

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

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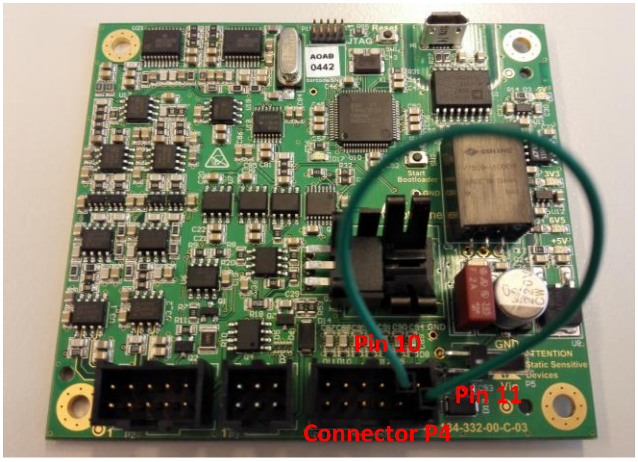
the optical feedback (OF) control. Tiny amounts of stray light still introduce an offset on the OF, shifting the actual set value. Although the remaining shift is canceled electronically on the EL-E-OF-A board, to achieve the efficient OF control, laser repetition rates >= 20 kHz are recommended.

6. Linearization: Focal power vs. analog voltage

In the firmware of the EL-E-OF-A controller board, we have implemented a feature that linearizes the focal power of the lens with the applied voltage. 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.



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

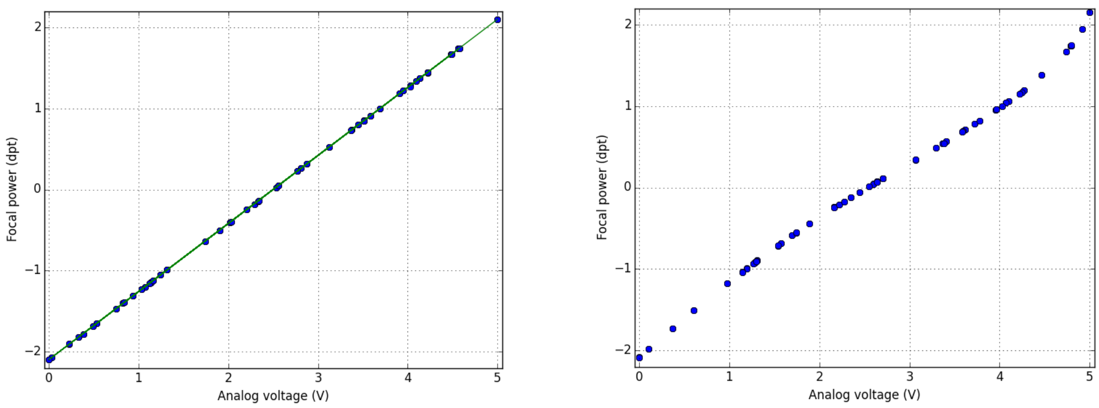


Figure 10: The measurement of focal powers (dpt) versus applied voltages. The linearization feature is enabled on the left and disabled (by default) on the right.

The main advantage of this feature is that when more than two marking systems need to be calibrated in a 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-

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position. Upon request, Optotune provides an Excel sheet 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 would be happy to advise you about the integration of Optotune's products into your design. Do not hesitate to contact us by e-mail at sales@optotune.com or by phone at +41 58 856 3000.

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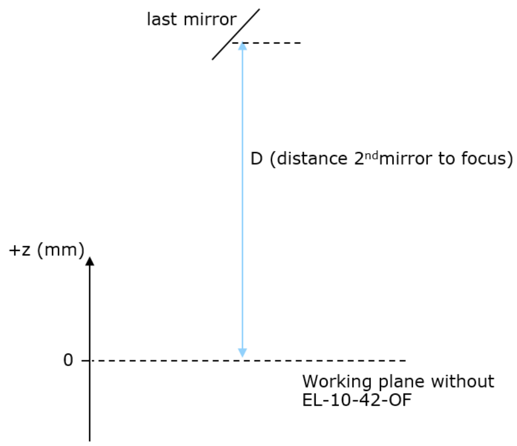
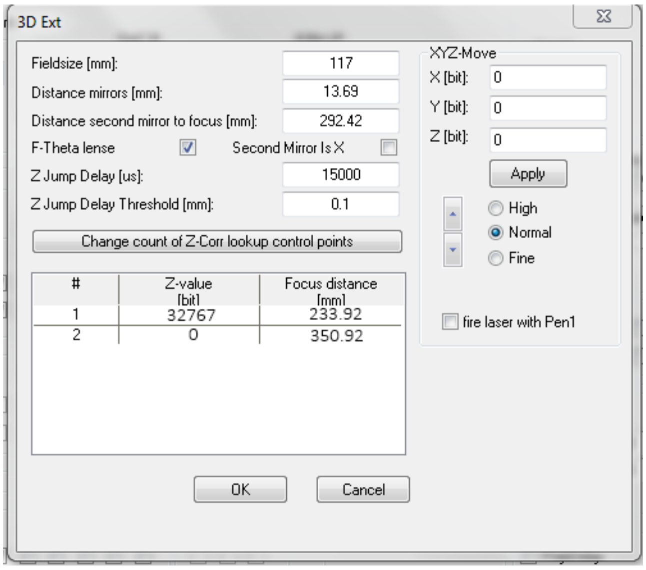
Appendix 1: How to perform z-calibration with EL-10-42-OF in SAMLight

The marking software SAMLight from SCAPS) allows for easy integration of the z-calibration via a look-up table, where the z-position of the laser spot is mapped against the control voltage. The method has been successfully tested in a standard marking system described earlier in this application note. The obtained precision is 500 µm. For higher precision, a beam profile measurement is recommended. The coordinate system is defined as indicated in the drawing below:



1. It is assumed that the distance D from the second mirror to the working plane is already known (in the given system, D = 292.42 mm). Before integrating the EL-10-42-OF, this has to be measured precisely, for example by using 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 result in 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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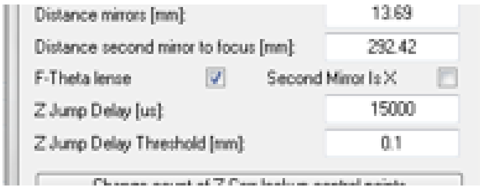
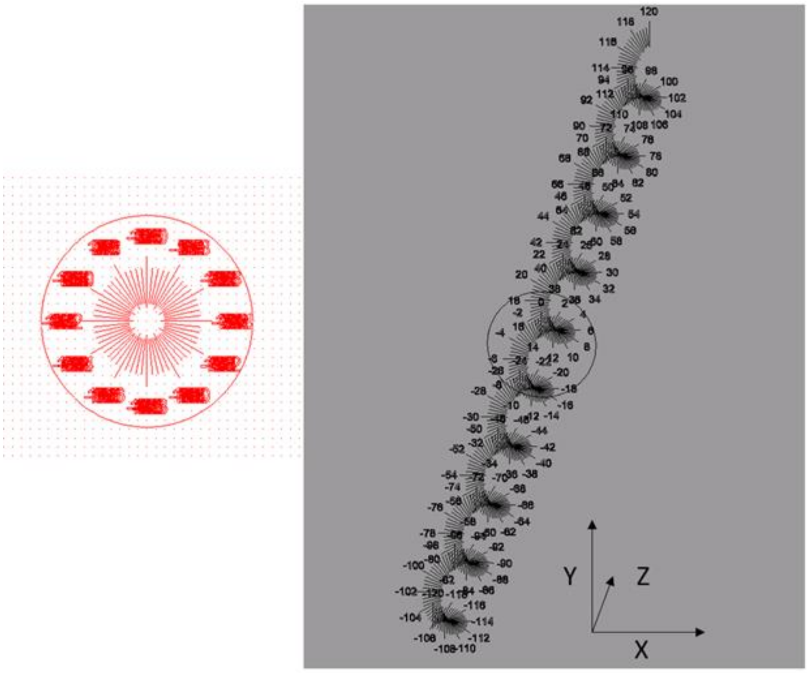
3. When using an f-theta lens, the corresponding check box in SAMLight has to be enabled.



4. Load the pre-defined marking job file "Calibrate_Optic3D_Circle_-120_to_120.sjf'" in SAMLight.



This job file serves as a vertical "ruler". It consists of lines ranging from -120…+120 mm in z-direction. The lines have 0.2 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 after applying "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 (for example anodized aluminum plate) at the first point of the final z-correction table (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.

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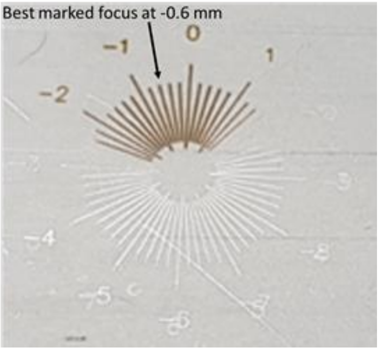
8. Extract the marked z-position values F_z from the marking sample. To do so it is helpful to analyze the samples under a standard microscope, for example by using 8x magnification. This increases the precision when locating the “best” line that was in focus.



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 should calculate D – (z-value). D is the distance from 2nd mirror to the working area. The final look-up table implemented in SAMLight, highlighted in red, looks as follows:

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

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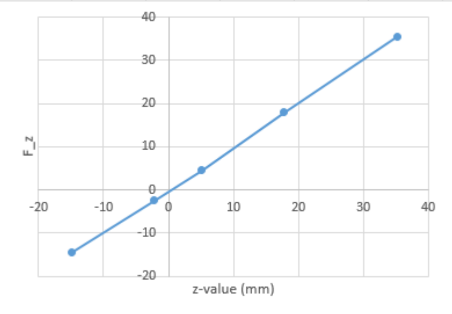
The two red columns are used in SAMLight as the final z-calibration look-up table. Note that in SAMLight, the "Focus distance (mm)" must be entered in ascending order:

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



Appendix 2: Response time and oscillation speed

Using the EL-E-OF-A electronics to control the EL-10-42-OF, we analyze three generic signal forms used in z-stepping laser processing: step, sinusoidal and triangular... 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 11 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.

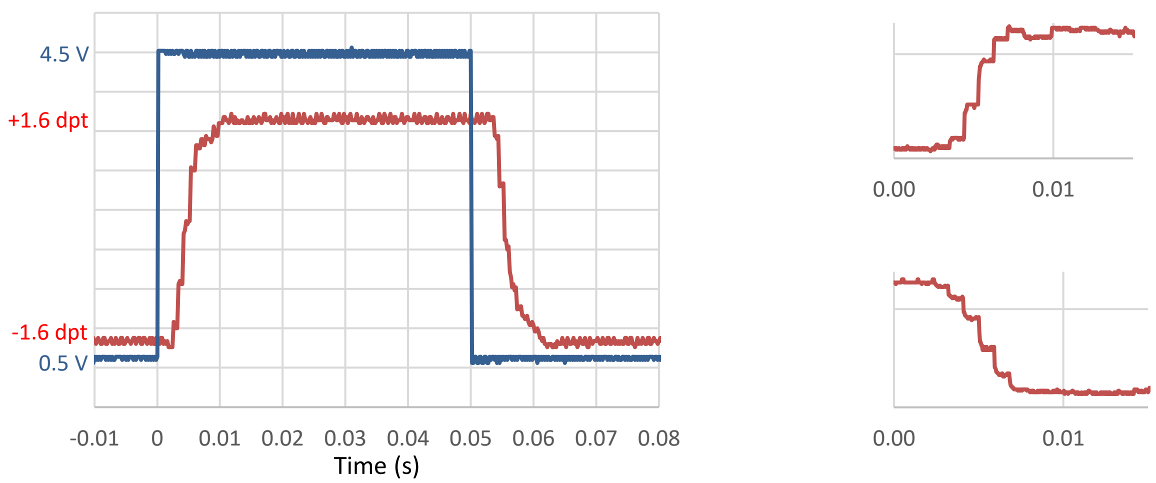


Figure 11: EL-10-42-OF step response of the optical feedback signal (red). The blue data shows the applied voltage step at the input of the EL-E-OF-A control board. The small figures on the left show a zoom on the rising and falling edges.

In a more detailed analysis we investigate the scaling of the response time with 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).

Optotune Switzerland AG | Bernstrasse 388 | CH-8953 Dietikon | Switzerland
Phone +41 58 856 30 00 | www.optotune.com | info@optotune.com

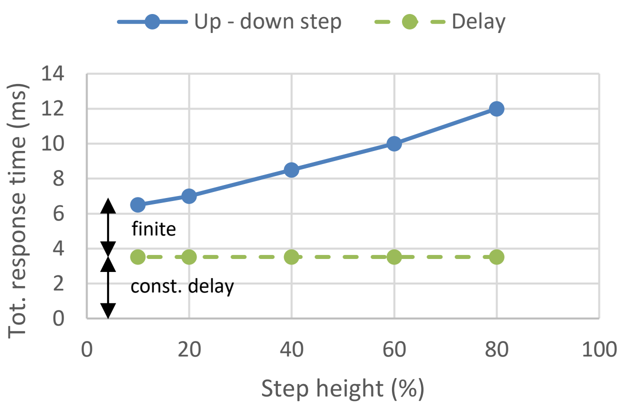


Figure 12: Total response time versus step height. It consists of two contributions: a constant delay and a finite rise time, which decreases with a smaller step height.

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.

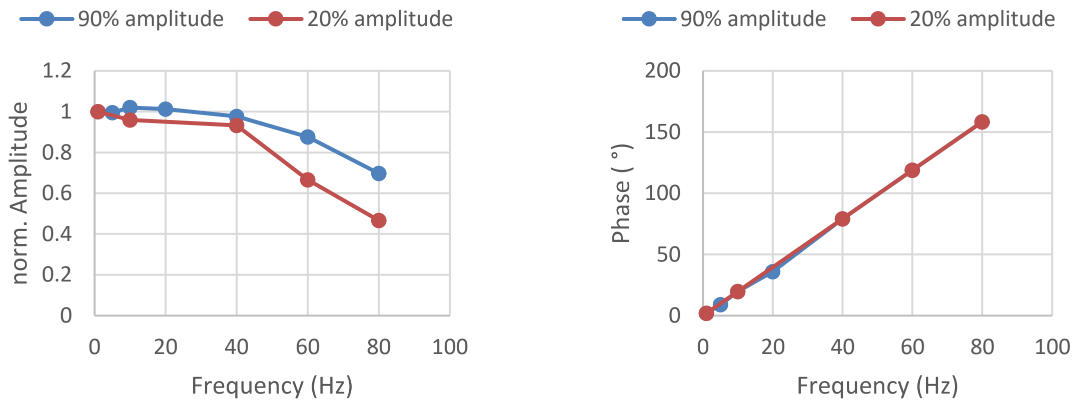


Figure 13: On the left, the normalized amplitude versus frequency for sinusoidal modulation. At 40 Hz, the amplitude starts to decrease. Within the measurement precision, the results are equal for the 90% and 20% amplitude. The right side shows the linear increase of relative phase, reflecting a constant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

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