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3D laser processing with tunable lenses

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Abstract

Optotune developed the tunable lens module EL-10-42-OF, enabling 3D laser processing without any mechanically moving part. Consequently, the time scale of focus change is very fast, in the range of several milliseconds.
Today, using laser light for material processing became a standard practice which is widely spread in industry. The basic idea is to focus a laser beam onto a fixed working plane which creates a spot of maximal intensity. Fixed glass optics in combination with movable galvo mirrors allow to scanning the whole working plane, however this is restricted to one specific working distance (2D) whereas in general objects are 3-dimensional.
In recent years, laser processing applications have sought to overcome this limitation and access the third dimension (z-axis), typically by using mechanically moving z-stages. In a complementary approach, Optotune offers a solution based on the company's well-established tunable lens technology, specifically optimized for laser processing applications.

Laser marking; laser processing; variable z-axis; three-dimensional; tunable lens

1. Main text

Using lasers for material processing became a standard tool which is widely spread in industry. The basic idea is to focus a laser beam onto a fixed working plane which creates a spot of maximal intensity. At this position the laser processes the surface to e.g. drill, engrave or mark the work piece. Fixed optics in combination with movable galvo mirrors allow to scanning the whole working plane in horizontal x- and y-direction. However this is restricted to one specific working distance (2D) whereas in general objects are 3-dimensional, see Fig. *1*.

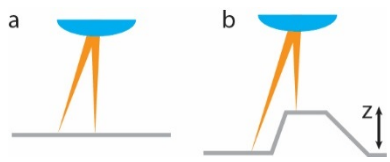

Fig. 1. (a) present the 2D situation where the laser spot can address one plane. As soon as the object is 3-dimensional, the laser spot has to be shifted along the z-axis, as shown in (b).

In recent years, laser processing applications try to tackle this limitation and access the third dimension (z-axis), typically by using rather bulky, mechanically moving z-stages. In a complementary approach, Optotune developed the tunable lens EL-10-42-OF, shown in Fig. *2* a). The lens has a 10 mm clear aperture and the optical coatings are optimized for 1064 nm laser wavelength with an overall transmission of 96%. The flexible membrane cannot be anti-reflection coated due to its changing curvature, leading to reflection between the air and membrane surface. The fluid and membrane are highly transparent materials leading to a very low absorption. Consequently, the damage threshold for ns- and ps-pulsed lasers, mostly used in the application, is relatively high > 2 J/cm2. This enables 3D laser processing without any mechanically moving part. Consequently, the time scale of focus change is very fast, in the range of several milliseconds.

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Based on Optotune's core technology, tunable polymer lenses, the z-position of the focus spot is changed by directly tuning the focal length of the EL-10-42-OF from -500 mm to +500 mm. The basic working principle of the tunable lens is illustrated in Fig. *2* b). It consists of a container that is filled with an optical fluid (refractive index n = 1.3) and sealed off with an elastic polymer membrane (n = 1.41). The lens core has an electromagnetic actuator that is used to exert pressure on the container, changing the deflection of the lens. This allows for controlling the focal length by changing the electrical current in the surrounding coils.

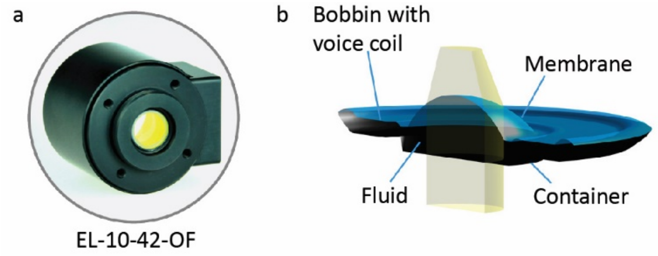

Fig. 2. In (a) the compact lens module EL-10-42-OF is shown. It has an outer diameter of only 42 mm. The basic components comprising the tunable lens core are illustrated in (b).

High focus stability and repeatability are essential parameters to guarantee consistent processing quality. If the laser is not focused on the work piece, the peak intensity quickly drops due to the increased spot size. Focus drift mainly originates from temperature effects. The volume of the fluid in the lens core slightly changes with temperature, leading to a change of deflection and hence focal length. Therefore, the EL-10-42-OF has an integrated optical feedback which measures the lens' deflection in-situ by detecting probe light of an LED on highly sensitive photo diodes. Thereby a position stability well below the Rayleigh length of a typical setup, the relevant figure of merit to compare with, is possible. In order to provide the necessary analog and digital electronics to control the EL-10-42-OF, Optotune specifically developed the controller card EL-E-OF-A. The hardware is optimized for the specific needs in laser processing applications such as a minimal sized board and convenient interfacing to external electronics. To control the focal length of the EL-10-42-OF through the EL-E-OF-A, an analog voltage signal between 0 and 5V is used.

Regarding optical integration it is obvious that the EL-10-42-OF has to be combined with additional fix optics since the range of focal length goes symmetrically from negative to positive. However the focal length of the total system has to be always positive to create a focus at finite distance. Fig. *3* shows the two principle schemes of integration which have also been realized with the demonstration setup. In a), the 2.5D approach with an f-theta lens is shown. In this configuration the f-theta lens provides the field flattening while the z-position of the laser spot is shifted by the EL-10-42-OF. The EL-10-42-OF is placed in the optical path before the scan head. The exact position is not very critical because the distance between the f-theta lens and the EL-10-42-OF has only a very small influence on the available z-tuning range. However changing the f-theta lens will affect the z-range and spot size. Generally, longer focal length leads to larger tuning range and spot size.

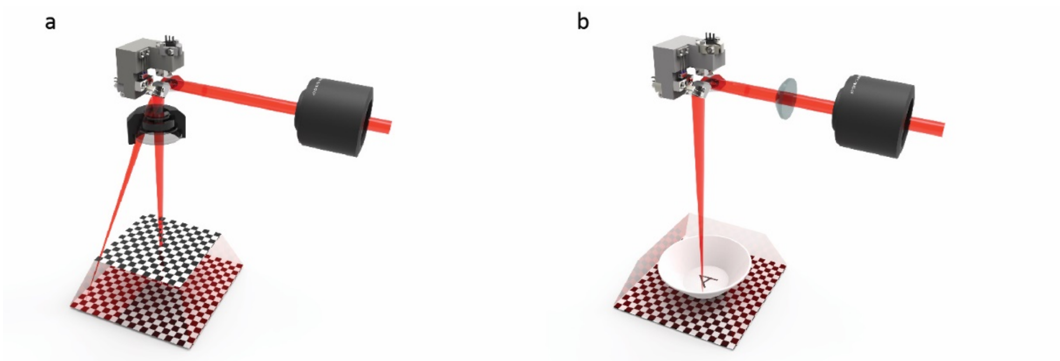

Fig. 3. The two principle schemes of optical integration are shown. In a), the EL-10-42-OF is placed before the scan head, in combination with an f-theta lens. In contrast, b) shows the situation without any f-theta lens. All elements, the additional focusing optics and EL-10-42-OF are placed before the scan head.

The integration for 3D processing is shown Fig. 3 b). Field-flattening and z-shift is accomplished by the EL-10-42-OF, hence the f-theta lens is not required anymore. The optical layout is based on off the shelf lenses. Essentially, the EL-10-42-OF is combined with a beam expander (L1, L2) and a final focusing lens L3 that creates the laser spot on the workpiece. This variable beam expander with the tunable lens allows for a specific design where the spot size remains constant over the full tuning range. A concrete example is presented in Fig. 4. The relevant parameter is the distance *d* between the tunable core element and the final focusing lens L3. Optimizing *d* allows for keeping the numerical aperture *~D/f* of the system and hence the spot size constant.

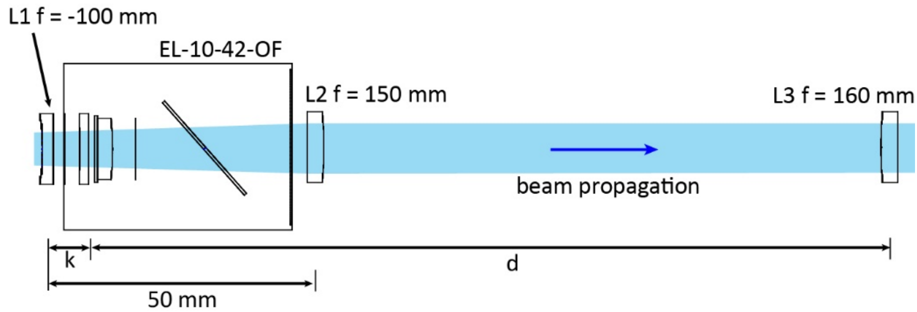

Fig. 4. Example of an optical design where the spot size remains constant over the full tuning range. The relevant parameter is the distance between the tunable lens core and the final focusing lens L3, called d.

In conclusion, Optotune offers a very compact plug-and-play solution with the EL-10-42-OF and EL-E-OF-A for 2.5D laser processing. First customers are close to market launch of a final product offering this feature. In a next step the optical design, software and control electronics have to be considered to achieve optimal performance in full 3D laser processing applications. First attempts in that direction are already initiated.