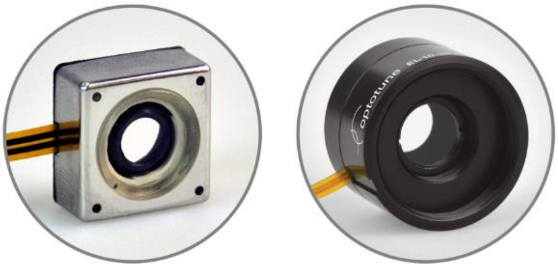
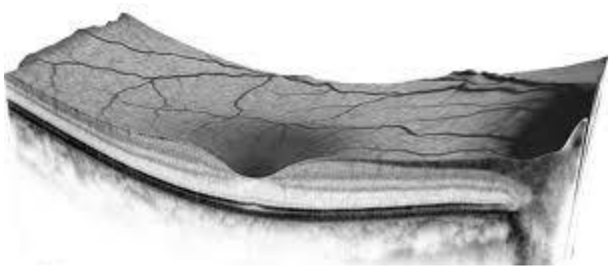
optotune
shaping the future of optics



Application note
Fast focusing for high resolution optical coherence tomography with Optotune products



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1. Introduction

Optical coherence tomography (OCT) is an optical signal acquisition and processing method. It captures micrometer-resolution, three-dimensional images from within optical scattering media (e.g. biological tissue). The images are acquired by an interferometric technique, typically employing near-infrared light. The use of light with relatively long wavelength allows it to penetrate several millimeters into the scattering medium. For example, OCT is used to produce detailed cross-sectional and 3D images of the eye. Commercially available OCT systems are employed in diverse applications, including art conservation and diagnostic medicine.

The first approaches of OCT were based on the principle of time-domain OCT (TD-OCT) (see Figure 1). A low-coherence light source is sent to a reference arm and a sample arm. The light in the reference arm is reflected by a movable mirror and the light in the sample arm is partially reflected from the sample. The interference of the back-reflected light is registered on a detector. The interference pattern contains the information of the path length difference of both arms and hence about the axial position of the sample. The interference is only visible when the path difference lies within the coherence length of the light source. By moving the mirror in combination with a transverse scan, a 3D image of the sample is reconstructed but with a very limited axial field of view, as mentioned above. The amount of data that can be captured is limited due to the relatively slow movement of the mirror.

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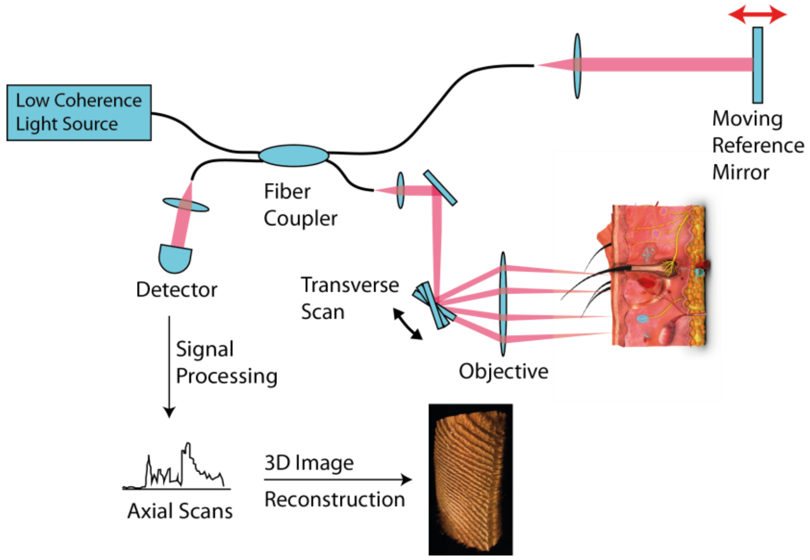

Figure 1: Generic Time Domain (TD-) OCT configuration. It requires a moving reference mirror for the axial scans (A-scans) and a transverse scanner for producing the top view scans (C-scans). The acquisition speed is relatively slow.

A major revolution in OCT came with the introduction of Fourier domain or spectral domain techniques (SD-OCT). In SD-OCT no moving mirror is required which makes the image acquisition about 100 times faster than in TD-OCT. In Fourier domain OCT the broadband interference is acquired with spectrally separated detectors. Due to the Fourier relation described by the Wiener-Khintchine theorem, the depth scan is calculated by a Fourier-transform of the acquired spectra, without movement of a mirror in the reference arm. Swept Source OCT (SS-OCT), another spectral domain technique, utilizes a fast and precise tunable light source, which is swept over the wavelength range, and a simple detector. Today the OCT market is largely dominated by SD-OCT and SS-OCT.

Despite of the fast progress, state-of-the art OCT system designers still have to make the choice between a large axial field of view and a small lateral resolution (see Figure 2a) or a high lateral resolution coming with a small axial field of view (see Figure 2b). This is mainly due to the fact that in SD-OCT as well as in TD-OCT, an acceptable resolution is only obtained with a small focal spot. A small focal spot is only possible with a high numerical aperture (NA) objective. Unfortunately, high NA comes with the penalty of a small depth of focus, resulting in a small axial field of view.

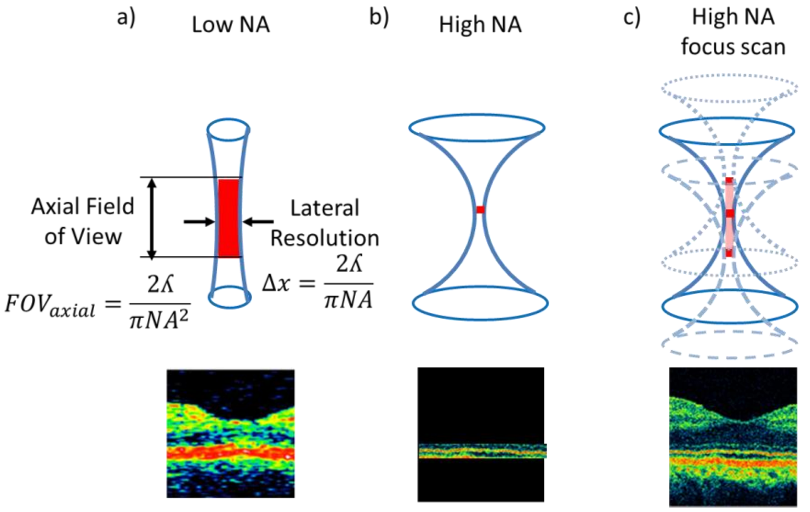

Figure 2: Trade-off between lateral resolution and axial field of view. a) focusing optics with low NA, b) focusing optics with a high NA and c) sample focusing optics with a high NA and an extended axial field of view due to a axial focus scan using the Optotune EL-10-30-C

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This is in contrast to the extended OCT depicted in Figure 2c where both, an extended axial field of view and a high lateral resolution are realized.
By performing an axial focus scan using focus tunable lenses, the resolution limiting trade-off is overcome. Without any movable mechanics, the Optotune EL-10-30 or EL-6-18 lens enables a single scan through a 2 mm thick sample within milliseconds.

In Figure 3 this *Extended OCT* is compared with different imaging techniques in terms of resolution and penetration depth.

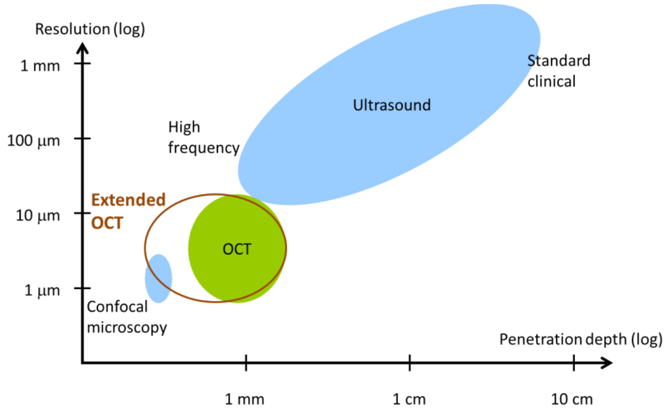

Figure 3: Extended OCT compared to standard imaging technologies.

The C-mount version of the EL-10-30-C lens is compatible with standard industrial objectives and can easily be combined with a high-NA sample focusing lens. Furthermore, an offset lens can be integrated in the EL-10-30-C to adjust the focal length range to the desired values. With a negative offset-lens, the focal range includes infinity, such that the EL-10-30-C can be placed in front of existing optics as a close-up lens for OCT systems requiring high optical resolution.
In the following, different implementations of Optotune products in OCT systems are described.

2. Application domains

2.1. Skin OCT - Extended optical coherence tomography

In conventional OCT systems the designer has to make a trade-off between lateral resolution and achievable field of view. Optotune’s EL-10-30-C or EL-6-18 enables a fast axial scanning of the focal spot through the sample, while maintaining the high NA and therefore a high lateral resolution. When combined with an x-y mechanical scanning of the sample or with a scanning Galvo mirror, high resolution 3D OCT is possible.

The extended scan range is especially interesting for skin OCT, since in contrast to eye OCT there are no limitations for the objective lens in terms of numerical aperture. An extended SD-OCT system is illustrated in Figure 4. Light from a low-coherence source is directed into a 2x2 fiber-optic coupler implementing a standard Michelson interferometer. The coupler splits the incident optical power into the sample and reference arms. Light exiting the reference fiber is incident upon a reference mirror and redirected back into the same fiber. Light exiting the sample fiber is incident upon a transverse scanning mirror mechanism designed to focus the beam on the sample and to scan the focused spot in one or two lateral directions.

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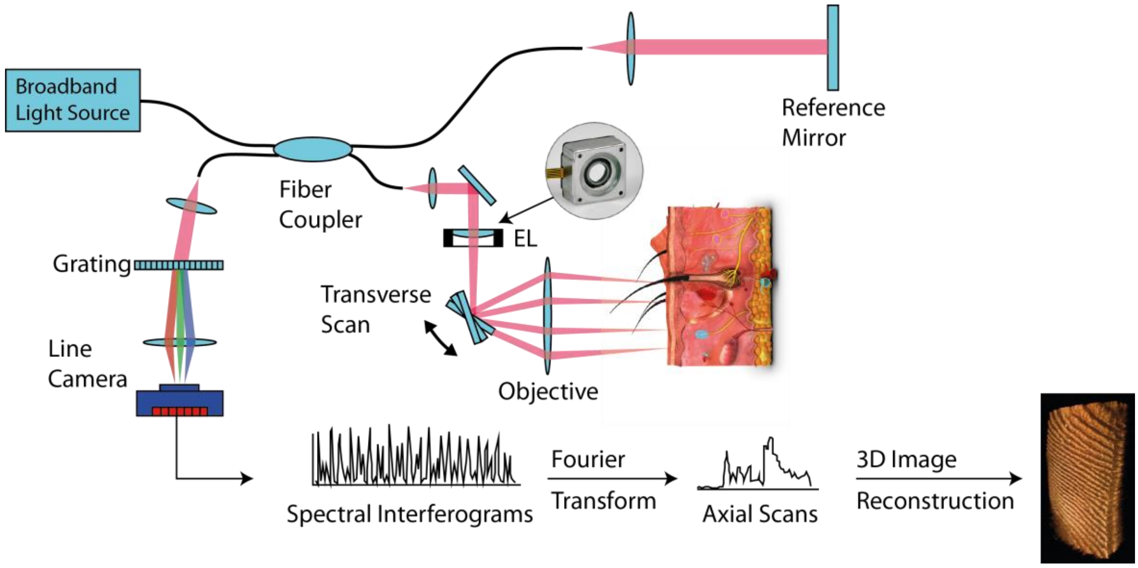

Figure 4: Schematic representation of an extended Spectral Domain SD-OCT for the investigation of tissue such as human skin. An electrically tunable lens placed before the scanning mirror allows extending the axial scan range while still maintaining the highest possible lateral resolution. As an example the fast electrical lens EL-6-18 is depicted.

The light which is reflected from the sample is redirected back through the same optical scanning system into the optical fiber, where it is mixed with the returning light from the reference arm. The combined light is spectrally separated by means of a grating and made to interfere on the surface of a fast CCD or CMOS line camera. The measured spectral interferogram is then Fourier transformed and out of the resulting axial scans a 3D image is reconstructed. Placing Optotune's tunable lens (EL) before the scanning mirror allows changing the starting point of the axial scans (A-scans). The A-scans of different depths are then stitched together (see Figure 5).

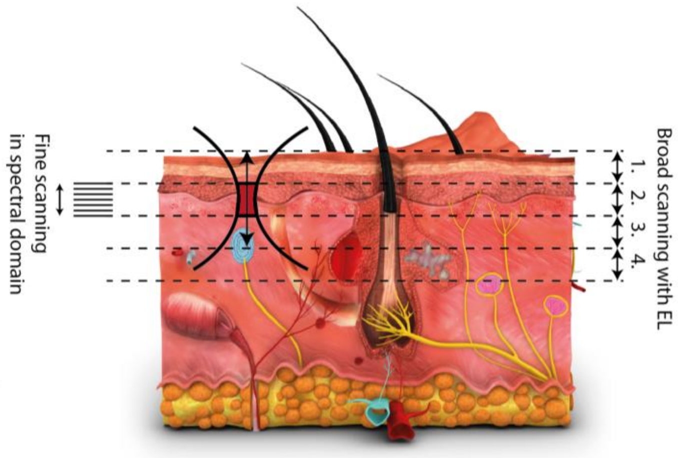

Figure 5: Illustration of stitching several axial (A-) scans together along the axial scan direction in order to obtain a large scan depth, while maintaining a good lateral resolution.

Figure 6 shows the principle of the extended axial scan range applied to SS-OCT systems, similar to SD-OCT with Optotune's tunable lens in front of the transverse scanning unit. In swept source OCT scanning, the light source is rapidly swept in wavelength and the spectral interference pattern is detected on a single detector as a function of time. The spectral interferograms obtained as a function of time then undergo a reverse Fourier transform to generate an A-scan image. Higher scanning speeds allow for denser sampling and better registration. While the tunable light sources are relatively expensive, the detection system becomes very simple.

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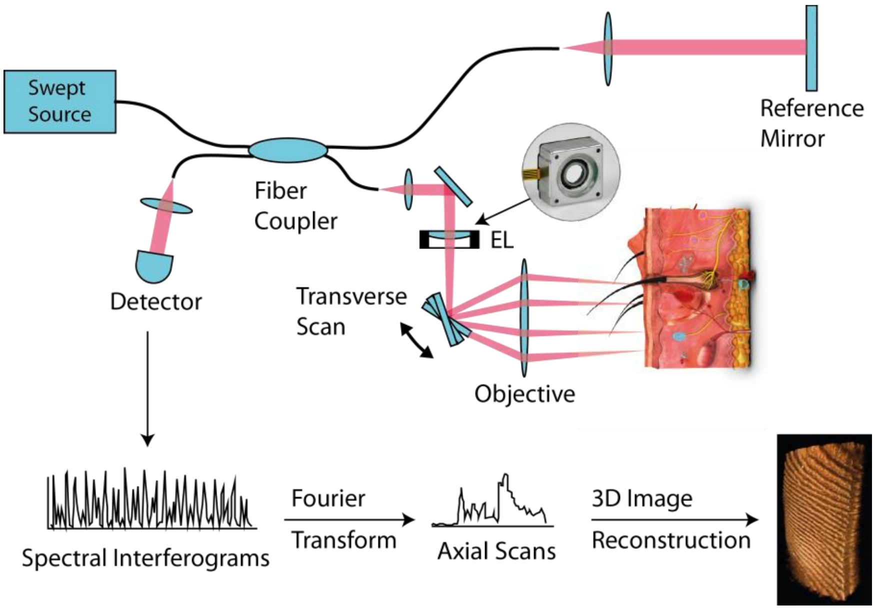

Figure 6: Schematic representation of a Swept Source (SS-) OCT for the investigation of tissue such as human skin. An electrically tunable lens placed before the scanning mirror allows extending the axial scan range while still maintaining the highest possible lateral resolution. As an example the fast electrical lens EL-6-18 is depicted.

2.2. Eye OCT

With Glaucoma, retinal and corneal diseases on the rise, Optical Coherence Tomography (OCT) increasingly finds its way into the ophthalmologist's practice. With OCT, each of the retina's distinctive layers is visible, allowing your ophthalmologist (Eye M.D.) to map and measure their thickness. These measurements help with early detection, diagnosis and treatment guidance for retinal diseases and conditions, including age-related macular degeneration and diabetic eye disease, among others.
Optotune's electrically tunable lenses enable OCT systems to focus on different focal planes within the eye and to simultaneously map cornea and retina (see Figure 7). They are compatible with spectral domain, swept-source and time-domain OCT. The fast tuning speed allows for tracking of the eyeball in real-time, leading to more reliable results. With no translational mechanics involved, the entire optics is compact and robust.

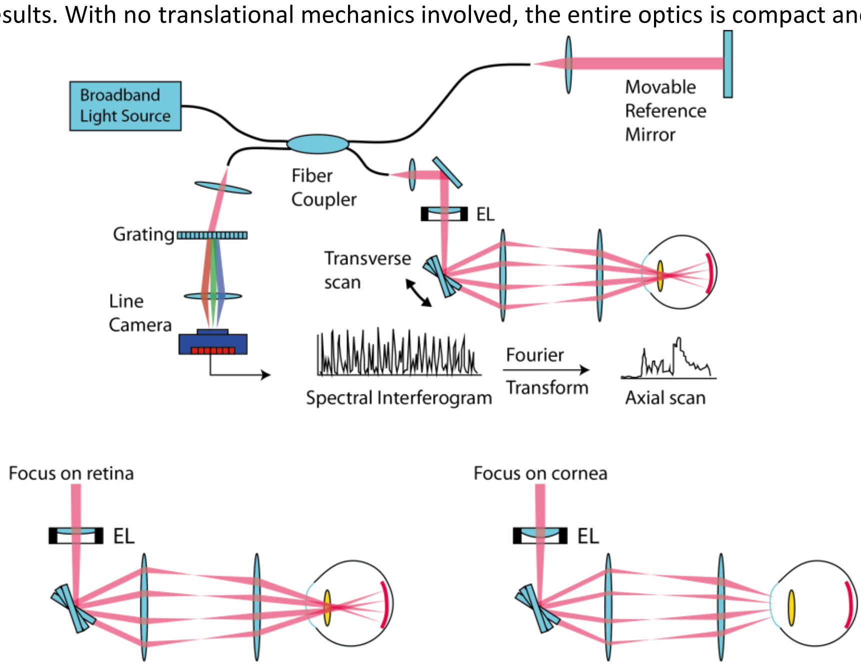

Figure 7: Schematic representation of a typical SD-OCT instrument for eye inspection. Placing the Optotune electrically tunable lens in front of the scanning mirror allows switching between retina and cornea.

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3. Configurations

3.1. Close-up configuration: EL-10-30-C in combination with fixed focal length lens

The EL-10-30-C with an integrated plano-concave offset lens is used as a close-up lens in combination with a fixed focal length lens to achieve an electronically controllable focusing unit with a high optical quality.

Figure 8 shows a comparison between a traditional focusing setup and a combination including a lens with a variable focal length. With the traditional approach using only a fixed focal length lens, one or several lenses have to be mechanically translated to achieve focusing through the sample. In contrast, when using a fixed focal length lens in combination with a tunable lens, all the elements of the fixed focal length lens stay at a fixed position. Only the curvature of the tunable lens and hence the focal length is varied, to achieve depth scanning through the sample. This makes the system much faster and more reliable.

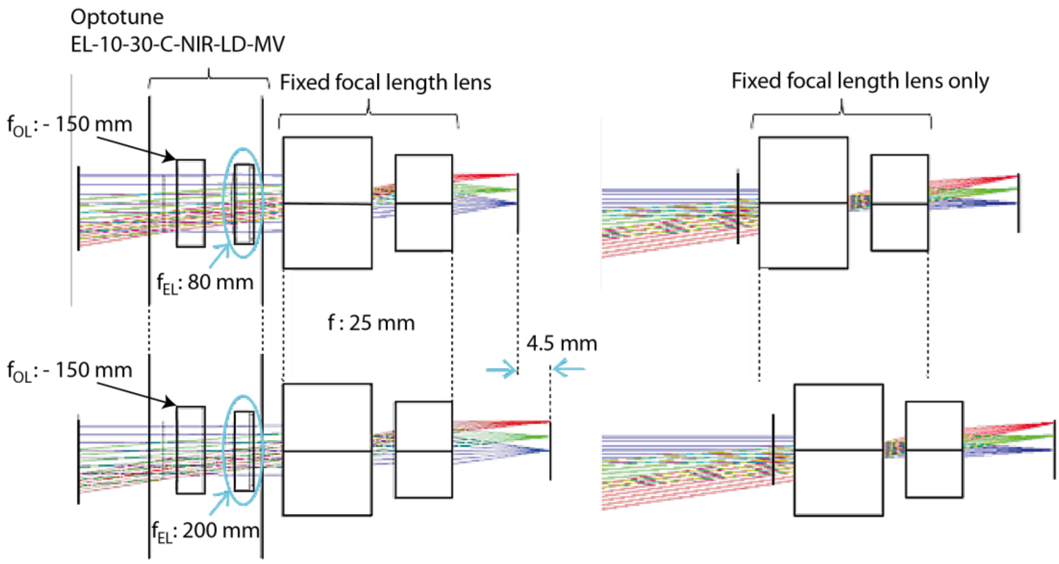

Figure 8: With a tunable lens, refocusing for different working distances (WD) is achieved by electrically changing the focal length of the tunable lens, without any translational movement

It is possible to integrate a -150 mm plano-concave fixed focal offset lens into the housing of the EL-10-30-C with the flat side facing the tunable lens. Depending on the filter thread of the fixed focal length lens an adapter is required between the EL-10-30-C with C-mount thread and the fixed focal length lens.

3.2. Standard products

Both the EL-10-30 and the EL-6-18 product families are suitable for OCT application. Table 1 gives an overview of selected products which may be used for OCT application.

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Standard products	Clear aperture	Tuning range[1]	Refractive index	Cover glass coating	RMS wave-front error[2]	Integrated offset lens	Temperature sensor
EL-10-30-VIS-LD	10 mm	+8to +22 dpt	1.30	400 – 700 nm	<0.50 λ	No	No
EL-10-30-NIR-LD	10 mm	+8 to +22 dpt	1.30	700 – 1100 nm	<0.50 λ	No	No
EL-10-30-C-VIS-LD	10 mm	+5 to +12.5 dpt	1.30	400 – 700 nm	<0.25 λ	No	Yes
EL-10-30-C-NIR-LD	10 mm	+5 to +12.5 dpt	1.30	700 – 1100 nm	<0.25 λ	No	Yes
EL-10-30-C-VIS-LD-MV	10 mm	-1.5 to +6 dpt	1.30	400 – 700 nm	<0.25 λ	Yes (-150 mm)	Yes
EL-10-30-C-NIR-LD-MV	10 mm	-1.5 to +6 dpt	1.30	700 – 1100 nm	<0.25 λ	Yes (-150 mm)	Yes
EL-10-30-C-1064-LD-LP	10 mm	-1.5 to +2.5 dpt	1.30	1064 nm	<0.12 λ	Yes (-150 mm)	Yes
EL-6-18-VIS-LD	6 mm	-2 to 20 dpt	1.30	400 – 700 nm	<0.1 λ	Yes (-50 mm)	Yes
EL-6-18-VIS-NIR	6 mm	-2 to 20 dpt	1.30	700 – 1100 nm	<0.1 λ	Yes (-50 mm)	Yes

Table 1: Overview of the standard products suitable for OCT applications.

4. Lens properties

4.1. Response time

For the EL-10-30 the rise time on a current step is about 2.5 ms. However, it takes about 15 ms until the lens has fully settled. Please see EL-10-30-C datasheet for detailed information including a graph with the optical response of the EL-10-30 to a current step. For faster response times, please also consider the smaller electrical lens EL-6-18, which is about 50% faster.

4.2. Coating options

The flexible membrane of Optotune's focus tunable lenses cannot be coated with standard processes as it needs to remain flexible. This means about 3-4% of reflection at the air/membrane interface must be expected. The cover glasses, however, can be coated adequately. The EL-10-30-C is available with two standard broadband coatings for VIS and NIR, but also narrow band coatings are available (e.g. for 355 nm or 1064 nm, see EL-10-30-C datasheet for detailed transmission curves). It is also possible to leave the cover glass away, if the lens is built into a dust-free environment. This might avoid parasitic reflections that often are an issue in OCT.

4.3. Wavefront quality dependence on orientation and focal length range

In principle, Optotune's focus tunable lenses exhibit a spherical lens shape (the nominal parameters can be found in the ZEMAX package, which is available for download on http://www.optotune.com/downloads).
Since the lens is made of an elastic material, the lens shape is influenced by gravity. With the lens lying horizontally (optical axis vertical) the RMS wavefront error of the EL-10-30-C-VIS-LD and EL-6-18 Series lenses is currently in the order of 0.1 λ (measured at 525 nm). With the lens standing upright (optical axis horizontal) a Y-coma term must be added. Furthermore, as can be seen in Figure 9, the lens exhibits a smaller wavefront error when it is less curved corresponding to longer focal lengths. Therefore, it is recommended to set the position of the fixed focal length lens such that the tunable lens can be operated in the long focal length range corresponding to low current values.

[1] Different focal tuning ranges available upon request.
[2] Wavefront error in RMS λ @525 nm, 0 mA current with optical axis horizontal (worst case)

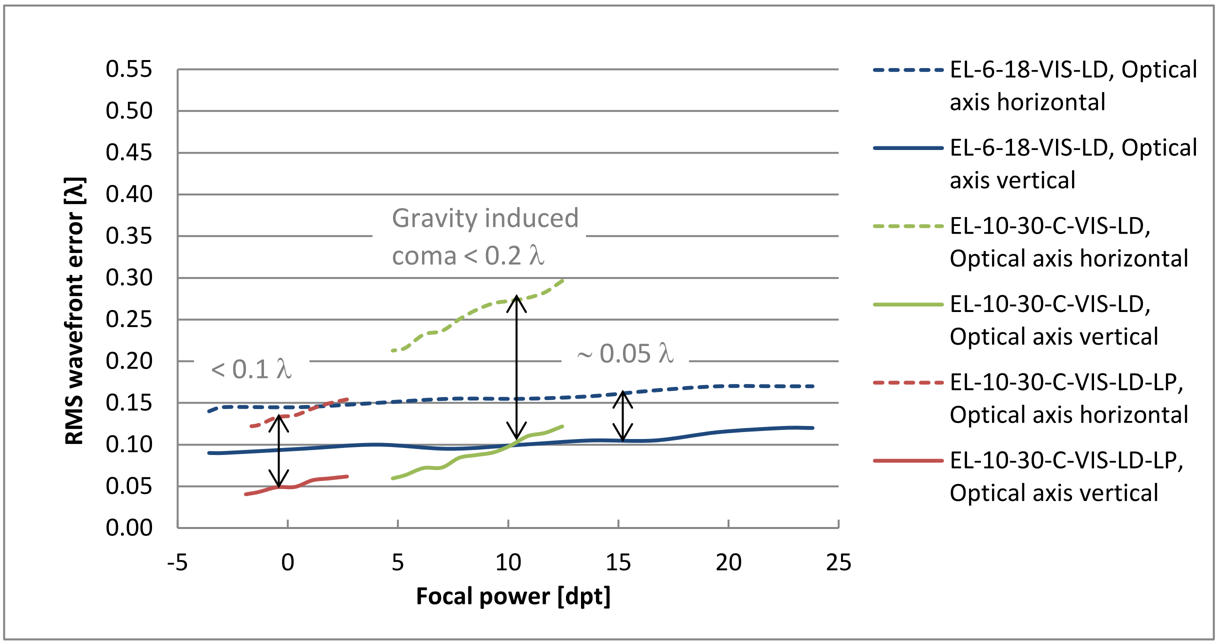

Figure 9: Wavefront measurement of the tunable lenses that are most suitable for OCT application (at 525 nm and 80% of clear aperture, defocus, tilt & sphere excluded)

The gravity induced Y-coma term depends on the size of the lens, the density of the liquid and the mechanical properties of the membrane. While it is insignificant with lenses of apertures below 5 mm, it accounts for about 0.1 λ and 0.2 λ for the EL-10-30-C-VIS-LD-LP and the EL-10-30-C-VIS-LD, respectively. Stronger membranes can be used to reduce Y-coma, however, this is at the expense of reduced focal tuning range.
Optotune is working on improved materials and lens designs to reduce the dependence on gravity.

4.4. Controlling the EL-10-30-C

The EL-10-30-C is current controlled (0 – 300 mA). Please refer to the EL-10-30 operating instructions for advice on available drivers. Unlike piezo systems, the EL-10-30 exhibits no hysteresis. The current through the coil induces a force, which is directly transferred onto the elastic membrane. There is no friction in the system. This means that at a constant temperature jumping between alternate current levels will always yield the same focal length. For simple focusing applications, a calibration using a look-up table is sufficient to achieve good repeatability. If the heating of the lens is significant, then using the built-in temperature sensor is recommended to calculate more precise look-up values.
For the EL-10-30-Ci lenses, Optotune's Lens Driver 4 offers a focal power mode, which makes use of calibration data stored in the lens (EEPROM). The absolute reproducibility achieved over an operating temperature range of 10 to 50°C amounts to typically 0.1 diopters. More details on the focal power mode are provided in the Lens Driver manual.

5. Low-cost, coherence length adjustable laser source using the LSR-3000

Additionally to the lens, Optotune's laser speckle reducer (LSR) can be used to build a low cost, narrow band, low coherence laser source for time-domain OCT systems. A low cost NIR laser diode can be directed onto the circularly moving diffuser of the Optotune LSR (see Figure 10). The Optotune diffuser reduces the coherence length of the laser light, which then can be coupled into the fiber-optic beam splitter. The main advantage of such a system is its simplicity and low cost. Furthermore, it enables the implementation of a light source with tunable coherence length by varying the actuation frequency of the moving diffuser.

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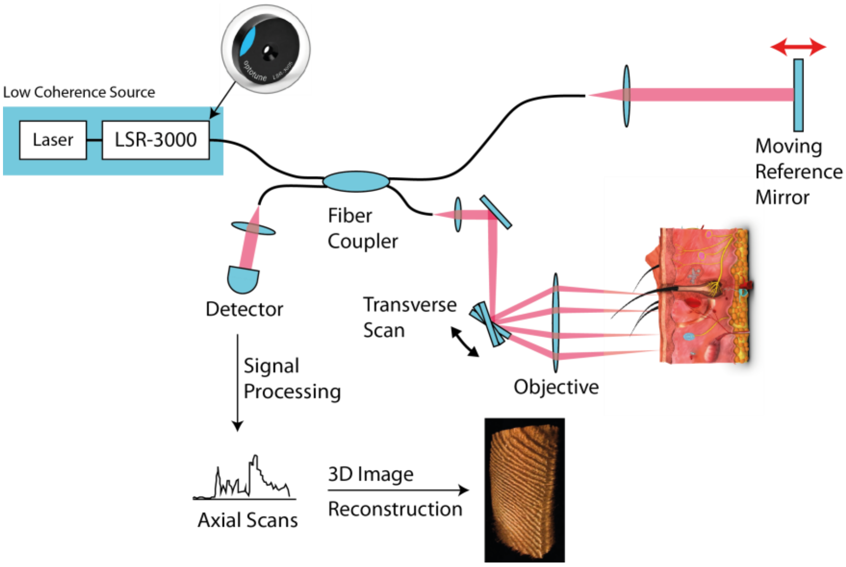

Figure 10: Low coherence laser source for time-domain OCT using a low cost laser source in combination with an Optotune LSR-3000.

6. Speckle reduction in detector by using the LSR-3000

Additionally, the Optotune laser speckle reducer LSR-3000 can be applied in front of the detector in a SD-OCT or TD-OCT system to remove speckle noise from the image and therefore enhancing the signal-to-noise ratio of the system.

7. Further information & support

For further information about the design of OCT systems using Optotune products, a quote or to support you in your applications engineering do not hesitate to contact us at sales@optotune.com or to call us at +41 58 856 3000.

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