

Fast Electrically Tunable Lens EL-10-30 Series



The curvature of this shape changing polymer lens can be adjusted by applying current. The focal length is accordingly tuned to a desired value within milliseconds. Optotune offers the EL-10-30 with the following options:

- Optical materials: High refractive liquid ($n_D=1.559$, $V=32$) & low dispersion liquid ($n_D=1.300$, $V=100$)
- Cover glass coatings: Visible anti-reflection coating (400-700 nm), near infrared coating (700-1100 nm)
- Housing: Compact 30x10.7 mm housing, 30x20 mm housing with C-mount threads

The following table outlines the specifications of our standard electrically tunable lens EL-10-30. Cover glass coatings and tuning range can be adapted on demand.

Mechanical specifications	EL-10-30 HR material	EL-10-30 LD material	EL-10-30-C (C-mount) LD material	
Clear aperture	10	10	10	mm
External diameter	30	30	30	mm
Thickness	10.7	10.7	20	mm
Weight	22.6	22.6	34.1	g
Lifecycles (10-90% sinusoidal)	>1'000'000'000	>1'000'000'000	>1'000'000'000	
Temperature sensor & memory	-	-	Yes (SE97B)	

Electrical specifications

Absolute maximum voltage	5	5	5	V
Control current	0 to 300	0 to 300	0 to 300	mA
Power consumption	0 to 1.1	0 to 1.1	0 to 1.1	W
Response time (10%-90% step)	<2.5	<2.5	<2.5	ms
Settling time	<15	<15	<15	ms

Optical specifications

Focal tuning range ¹	+20 to +60	+45 to +120	+80 to +200	mm
Dispersion (at 20°C)				
486 nm	1.572	1.302	1.302	
589 nm	1.559	1.300	1.300	
656 nm	1.554	1.299	1.299	
800 nm	1.546	1.298	1.298	
1065 nm	1.541	1.297	1.297	
1550 nm	1.535	1.296	1.296	
Abbe number V	32	100	100	
Lens type	plano-convex	plano-convex	plano-convex	
Transmission spectrum	see Figure 6	see Figure 6	see Figure 6	
Optical damage threshold @ 1064 nm	10	10	10	kW/cm ²
Wavefront error (@525 nm, 0mA)	<0.3 / <0.8	<0.2 / <0.5	<0.15 / <0.25	λ RMS
Optical axis vertical / horizontal				
Centration	<2	<2	<2	arcminutes
Polarization	preserving	preserving	preserving	

Thermal specifications

Storage temperature	[-40,+85]	[-40,+85]	[-40,+85]	°C
Operating temperature	[-5,+65]	[-20,+65]	[-20,+65]	°C

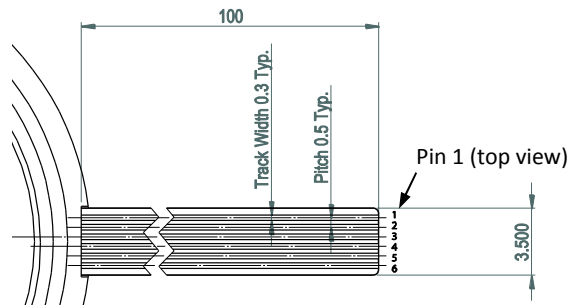
¹ Different focal tuning ranges available upon request

The EL-10-30 comes in two different housings: Compact and C-mount. While the compact housing is preferably mounted in a 30 mm ring, the C-mount housing has threads on either side. Furthermore, the C-mount version accommodates space to insert an offset lens of 12 or 12.7 mm diameter. The working principle of both versions is identical.



Electrical connection

While the compact EL-10-30 has a cable with two copper wires, the EL-10-30-C has an FPC connection, which is compatible with Molex 0.5 mm pitch 6 way FPC backflip connector (P/N 503480-0600). Samples ship with an adaptor for easy soldering. The EL-10-30-C features an SE97B temperature sensor with 256 bytes of memory.



Pinning		
Position	Function	SE97B Pins
1	SE97B Gnd	1-4
2	Lens (- pole)	-
3	Lens (+ pole)	-
4	SE97B SDA	5
5	SE97B SCL	6
6	SE97B Power	8

Optical layout

Figure 3 contains the information needed to model the EL-10-30 for simulations. A more detailed design guide and a ZEMAX plug-in can be downloaded from

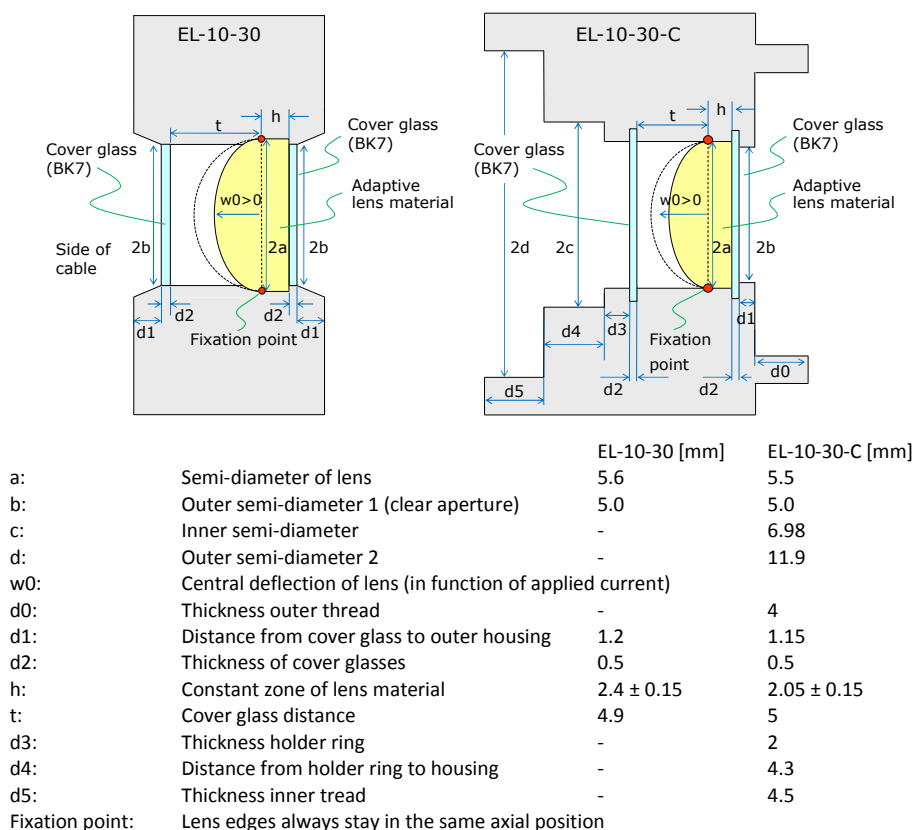


Figure 3: Optical layout of the EL-10-30 and EL-10-30-C with corresponding terminology

Using offset lenses

In the C-mount version of the EL-10-30 the protective cover glass can be replaced by an offset lens of 12 or 12.7 mm diameter. This allows shifting the focal length range to any desired value. For example, adding an offset lens with $f = -150$ mm to the EL-10-30-C-VIS-LD will yield a focal length range of about -600 mm to infinity to +170 mm ($1/f_{res} = 1/f_{EL-10-30} + 1/f_{offset}$). The design of the EL-10-30-C is optimized for good alignment of the tunable lens and the offset lens. The maximal thickness of the offset lens may be 4.7 mm.

Working principle

The EL-10-30 is a shape-changing lens. It consists of a container, which is filled with an optical fluid and sealed off with an elastic polymer membrane. The deflection of the lens is proportional to the pressure in the fluid. The EL-10-30 has an electromagnetic actuator that is used to exert pressure on the container. Hence, the focal distance of the lens is controlled by the current flowing through the coil of the actuator.

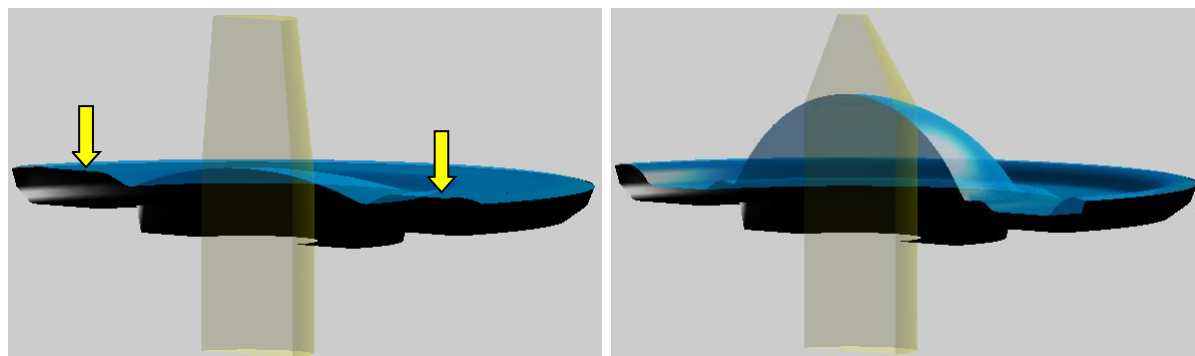


Figure 4: Working principle of the EL-10-30

Focal length versus current

The focal length of the EL-10-30 decreases with increasing current. The starting point at zero current is set during production and can be varied from lens to lens, whereas the maximal value is 500 mm. The slope of the focal length decrease is influenced by the mechanical properties of the membrane, which can also be varied on request to achieve different ranges of focal length. In open loop systems, a calibration of the lens with look-up tables is recommended.

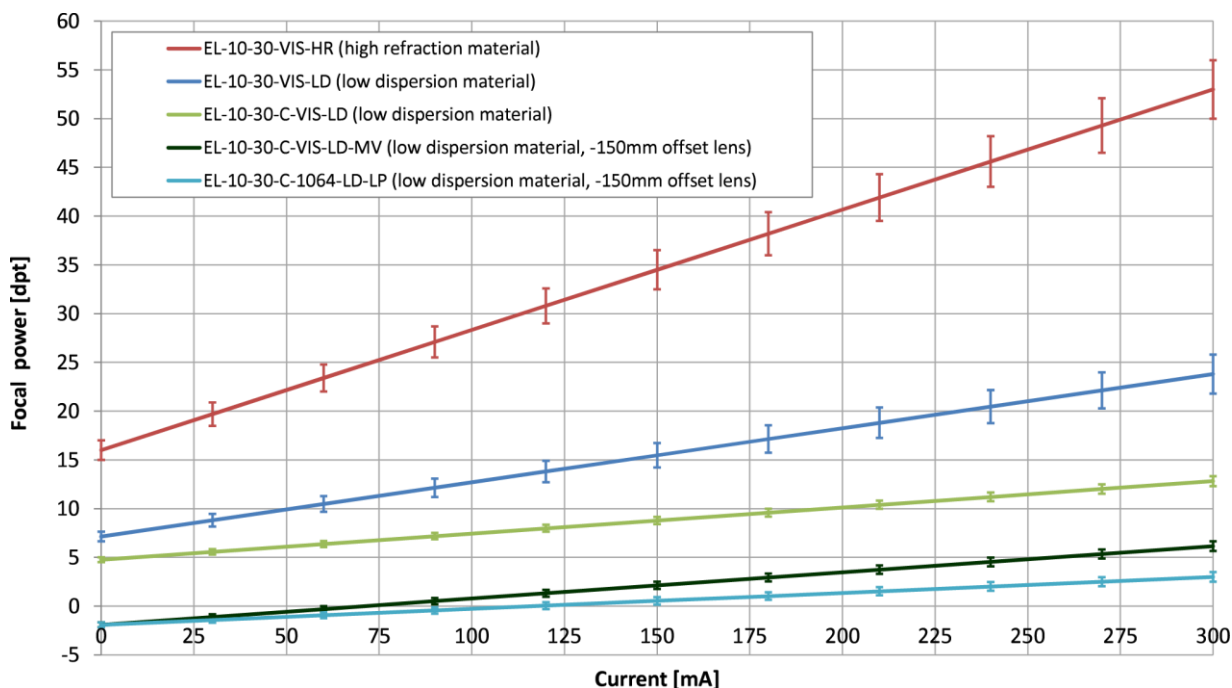


Figure 5: Typical relation of optical power (in diopters) to current of the most common EL-10-30 variations. The error bars show the standard deviation from lens to lens.

Transmission range

Both the optical fluid and the membrane material are highly transparent and hardly absorbing in the range of 250 – 2500 nm. As the membrane is elastic it cannot be coated using standard processes, hence a reflection of 3 – 4% is to be expected. Cover glasses can be coated as desired. The figures below show the transmission spectrum for our two standard broad-band coatings (visible and near infrared) as well as two custom narrow-band coatings:

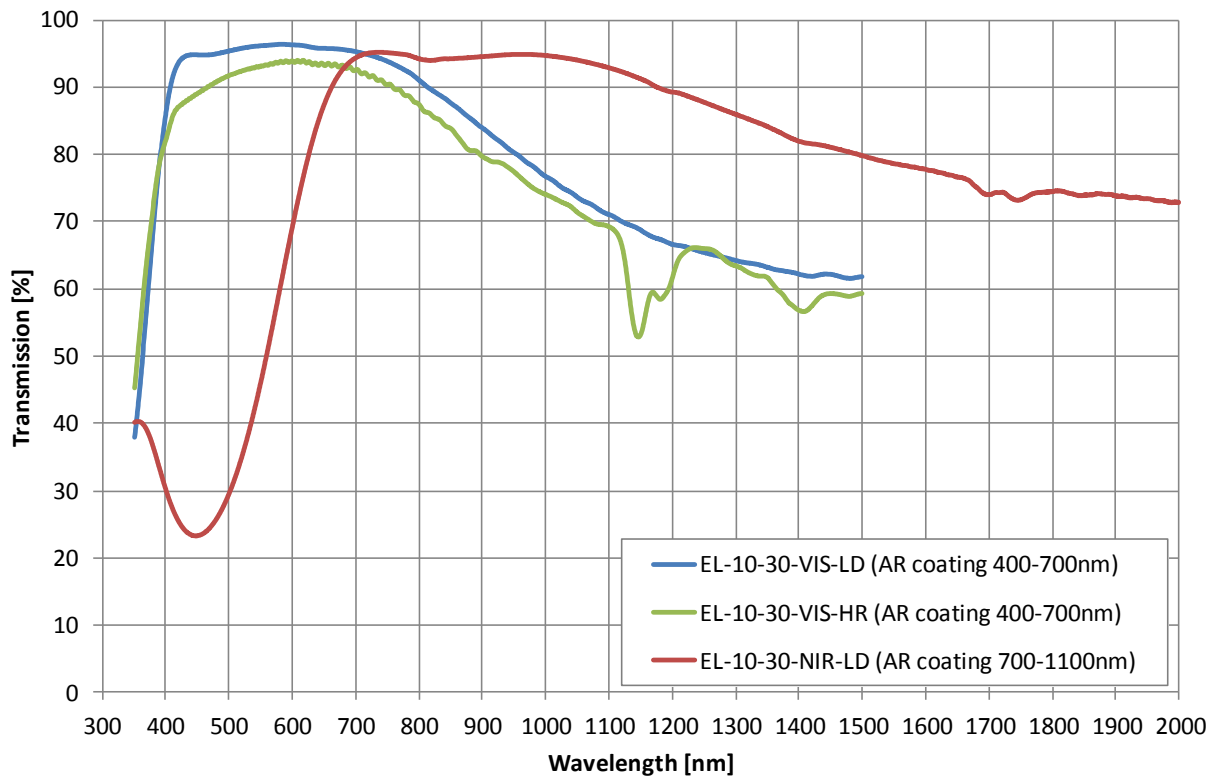


Figure 6: Transmission spectrum of the EL-10-30 for standard broad-band coatings

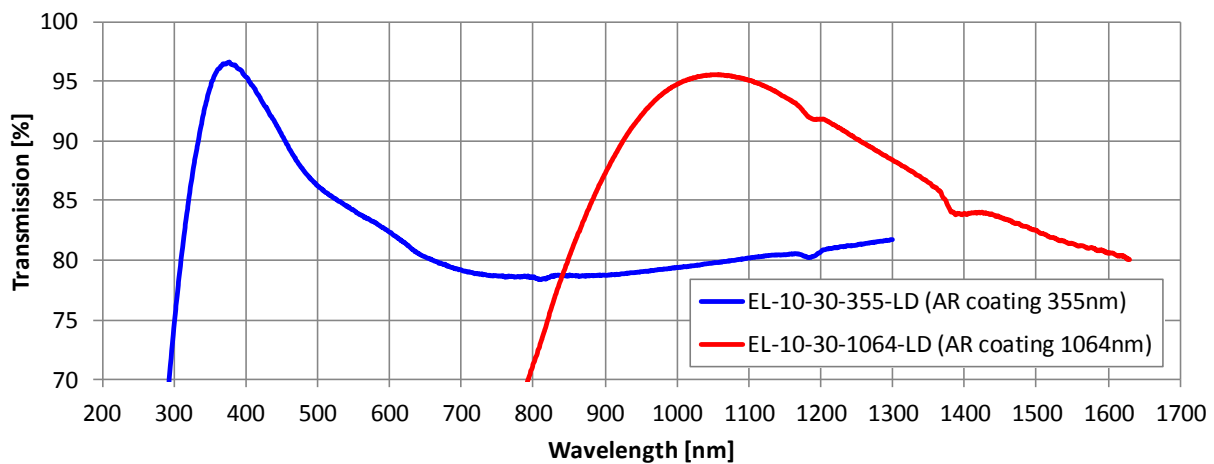


Figure 7: Transmission spectrum of the EL-10-30 for custom narrow-band coatings

The following graph represents the transmission of the lens material only² (i.e. assuming perfect cover glasses).

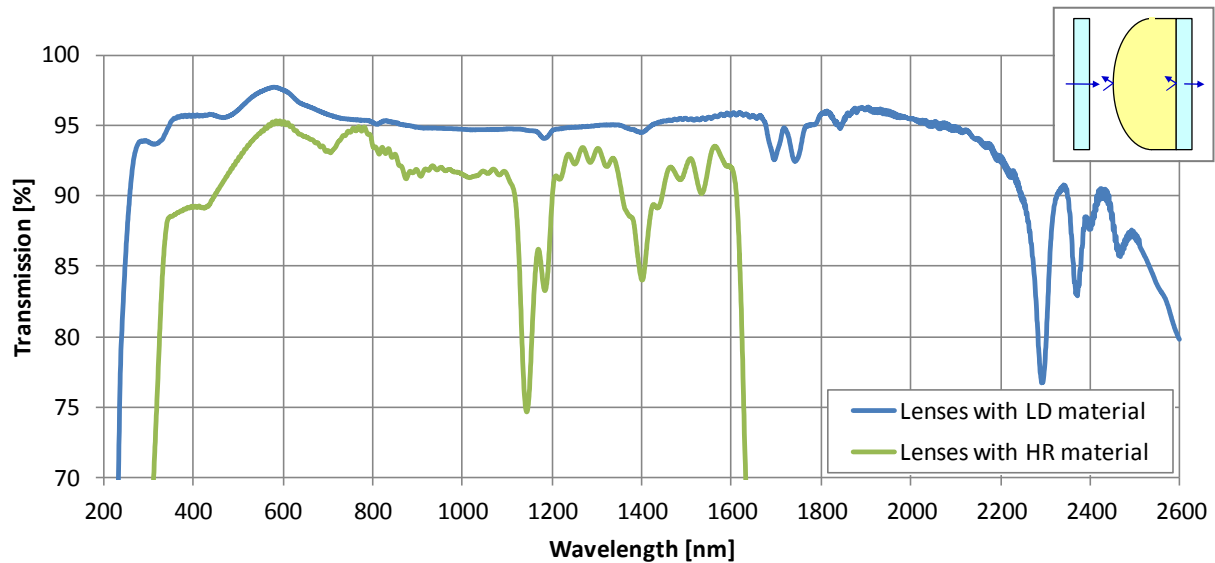


Figure 8: Transmission of the EL-10-30 assuming 100% transparent cover glasses

Wavelength [nm]	EL-10-30-VIS-LD	EL-10-30-VIS-HR	EL-10-30-NIR-LD	EL-10-30-355-LD	EL-10-30-1064-LD	Lens with LD Material ²	Lens with HR Material ²
355	40.4	48.3	40.3	95.5	49.8	95.4	88.5
375	61.7	67.4	38.2	96.6	50.7	95.7	88.9
405	88.3	83.5	29.1	95.0	66.8	95.7	89.3
440	94.8	88.4	23.5	91.6	88.6	95.8	89.5
488	95.1	91.2	26.9	87.0	80.2	95.8	91.9
514	95.6	92.3	32.9	85.6	67.8	96.5	93.1
532	95.9	92.8	38.7	84.9	60.7	97.0	93.9
632	95.9	93.4	81.8	80.9	47.3	96.8	94.6
650	95.7	93.4	87.2	80.3	48.2	96.5	94.2
680	95.6	93.4	92.6	79.5	50.9	96.1	93.7
730	94.5	91.7	95.2	78.8	58.3	95.6	94.0
808	90.5	86.6	94.1	78.4	72.7	95.1	93.5
830	89.0	85.4	94.1	78.8	77.1	95.4	93.0
850	87.7	84.0	94.3	78.8	80.4	95.3	92.9
880	85.5	80.7	94.4	78.7	84.8	95.1	91.4
905	83.6	79.5	94.6	78.8	87.9	94.9	91.6
915	82.9	79.0	94.7	78.8	89.0	94.9	91.7
975	78.5	75.5	94.9	79.3	93.7	94.8	91.9
980	78.3	75.2	94.9	79.3	94.0	94.8	91.7
1030	74.9	72.8	94.4	79.6	95.4	94.7	91.4
1064	72.9	70.7	93.8	79.9	95.5	94.8	91.7
1070	72.7	70.3	93.7	80.0	95.4	94.8	91.9
1310	64.0	63.2	85.7	81.9	88.0	95.1	93.1
1540	NA	NA	78.9	83.5	81.5	95.6	90.4
1550	NA	NA	78.7	83.6	81.4	95.6	92.1

Table 1: Transmission values of the EL-10-30 for common lasers

² The transmission of the „lens material only“ is put together from measurements of several lenses with differently coated cover glasses, whereas the three interfaces of „air to coverglass“ were removed mathematically.

Damage thresholds

The nominal specification of the lens materials used is 25 kW/cm^2 . However, this number has not yet been sufficiently tested. Good results have been achieved with the following lasers:

- 1070 nm, 200 W CW on a 3 mm beam diameter (equivalent to 2.2 kW/cm^2)
- 980 nm, 75 W CW on a 1.5 mm beam diameter (equivalent to 4 kW/cm^2)
- 1064 nm, 20 ns-pulsed at 50 kHz, 10 W average power on a 0.05 mm beam diameter (10 J/cm^2)
- 355 nm, 20 ns-pulsed at 50 kHz, 7 W average power on a 0.05 mm beam diameter (7 J/cm^2)
- 1064 nm, 12 ps-pulsed at 8.2 MHz, 38 W average power on a 2 mm beam diameter ($147 \mu\text{J/cm}^2$)
- 850 nm, 140 fs-pulsed at 80 MHz, 3 W average power on a 6 mm beam diameter ($0.13 \mu\text{J/cm}^2$)
- 345 nm, 500 fs-pulsed at 200 kHz, 0.5 W average power on a 3 mm beam diameter ($3 \mu\text{J/cm}^2$)

While no heating up of the lens is observed with the pulsed lasers, a 200 W CW laser does heat up the lens, resulting in a focus drift, which stabilizes after about 20 seconds. To avoid heating up of the lens due to reflections hitting absorbing surfaces, it is advised to calculate such reflections and preferably not use more than 8 mm of the clear lens aperture.

Wavefront quality

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).

As the membranes used are elastic, the lens shape is influenced by gravity. With the lens lying horizontally (optical axis vertical) the RMS wavefront error of the EL-10-30 Series lenses is currently in the order of 0.1λ (measured at 525 nm), allowing for high quality imaging e.g. in microscopy. With the lens standing upright (optical axis horizontal) a Y-coma term must be added.

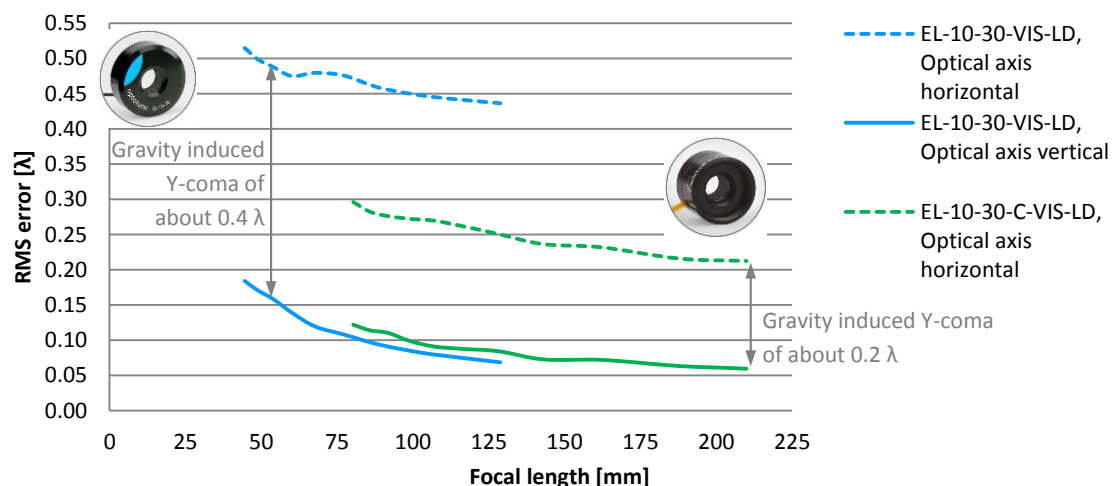


Figure 9: Wavefront measurement of a typical EL-10-30-VIS-LD and EL-10-30-C-VIS-LD (at 525 nm and 80% of clear aperture, defocus, tilt & sphere excluded)³

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 0.2λ for the C-mount version and 0.4λ for the compact version of the EL-10-30. The difference between the two is the design of the membrane. The stronger membrane of the EL-10-30-C reduces the gravity effect, however at the expense of focal tuning range (7.5 diopters for the EL-10-30-C, versus 13.9 diopters for the EL-10-30).

³ Data for the EL-10-30-C optimized for laser processing applications, the EL-10-30-C-1064-LD-LP, with less gravity induced Y-coma, can be found in the application note *Fast axial focusing in laser processing with Optotune's focus tunable lenses EL-10-30-C*

Temperature effects

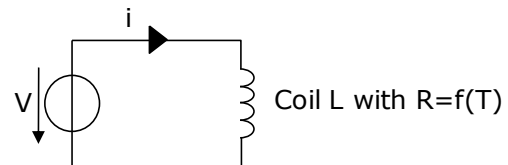
Heating up of the lens has two consequences: First, the refractive index of the optical fluid decreases. Second, the fluid expands in volume. While the first effect would increase the focal distance, the second effect reduces it. With the EL-10-30 design, the second effect prevails. The focal distance decreases by approximately 0.6 diopters per 10°C temperature increase.

This temperature effect is systematic and reproducible. This means the focal length can be controlled if the temperature is known. The EL-10-30-C actually has a built-in temperature sensor (SE97B). The compact EL-10-30 does not have that sensor, but measuring the resistance of the coil (voltage divided by current) can serve as a proxy for the temperature in the lens.

Heating up of the lens can occur at room temperature if driven at high currents or due to absorption of high power laser light. In such cases the lens is preferably mounted using heat-conducting metal clamps. For custom designs it is possible to balance the two temperature effects such that the focus shift becomes minimal at a certain focal length.

Current control vs. voltage control

In principle, the EL-10-30 can be driven using a DC voltage (e.g. even a simple battery). However, as the lens incorporates an electromagnetic actuator, the force applied to the lens (and with that the focal distance) depends on the current flowing through the coil. As with all electronics, the resistance of the coil changes with temperature (12.5 Ohm at 25°C). So if a voltage controller is used, the focal distance may not be reproducible or drift away. This is especially the case at currents >200 mA where this effect can easily be in the range of 10%. Note that this temperature effect is visible in the order of seconds and has nothing to do with the expanding of the optical fluid described above, which is in the order of minutes.



Coil resistance = $f(T)$
EL-10-30-VIS-LD

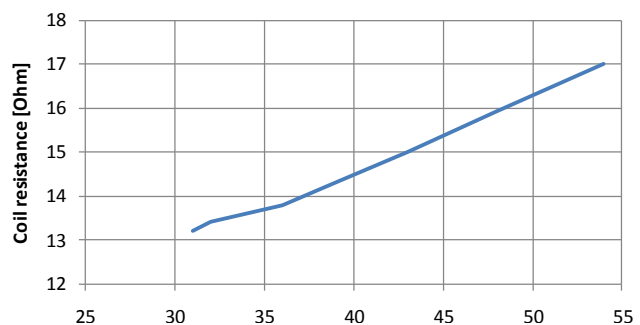


Figure 10: Coil resistance increases with temperature

Recommended drivers/power supplies

Optotune has launched its own high-precision USB driver with a resolution of 0.1 mA. It includes the I2C readout of the temperature sensor, which can be used for temperature compensation.



There are also many alternative off-the-shelf products available that can be used to control the EL-10-30:

- Precision constant current driver for laser diodes with external control via 0-5 V analog signal (e.g. Edmund Optics NT56-804 or NT84-355)
- For high precision applications (0.1 mA resolution) with manual control: TTi QL355
- For high precision applications (0.1 mA resolution) with USB/RS232 computer control: TTi QL355P
- For low precision applications (1 mA resolution) with manual control: TTi EL301R
- For low precision applications (1 mA resolution) with USB computer control: Quakko HY3005DP

The lens can also be driven using pulse width modulation (PWM) with a frequency between 20 kHz and 50 kHz. Another very useful component is the ADN8810 programmable precision current source of Analog Devices, which features 12 bits of resolution and can be controlled with an SPI interface.

Response time

The rise time on a current step is about 2.5 ms. However, it takes about 15 ms until the lens has fully settled. The following graph shows the optical response on a current step measured using the astigmatic lens approach with a cylinder lens and a quadrant diode⁴.

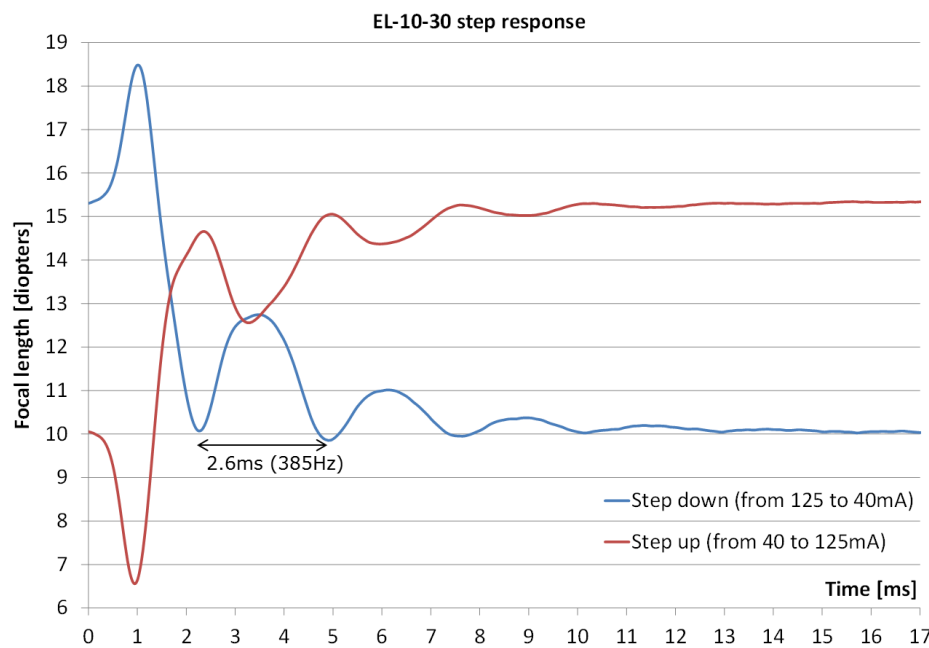


Figure 11: Optical response of the EL-10-30 to a current step from 40 to 125 mA and back

This system is slightly over-damped and shows a resonant frequency at about 385 Hz. The latter can be very interesting if operation in resonance is desired. To achieve a shorter settling time, however, it is better to remove this frequency from the step function. Also, settling time can be improved by applying an overshooting step function. Tests show that the dynamics of the lens are similar in both directions and across different current ranges.

For faster response times, please consider the smaller electrical lens EL-6-18, which is about 50% faster.

Reproducibility

Unlike piezo systems, the EL-10-30 exhibits no hysteresis. The current through the coil induces a force, which is directly transferred onto the 100% elastic membrane. There is no friction in the system. This means that jumping between alternate current levels will always yield the same focal length. This could be confirmed after running 10 million full range cycles.

So basically the reproducibility is limited by the precision of the electronics. For high precision applications a controller with 12 bits is recommended. Assuming a linear relation between current and focal distance, this would mean that the focal distance of e.g. an EL-10-30-VIS-LD would be accurate to $(120 \text{ mm} - 45 \text{ mm}) / 4096 = 18 \text{ } \mu\text{m}$. What needs to be taken into account, though, is a potential heating up of the lens when it is operated at high currents over a long period of time.

⁴ See Donald K. Cohen „Automatic focus control: The astigmatic lens approach“, Applied Optics Vol. 23, No. 4, February 15, 1984

Atmospheric pressure and low temperature performance

By working principle, the atmospheric pressure has no influence on the lens. This has been validated down to 10^{-4} mbar. Furthermore, the EL-10-30 with LD material is suitable for low temperature operation. The lens is tunable down to temperatures as low as 230 K. The response time of the lens increases for lower temperatures (e.g. 3 s at 250 K and 60 s at 230 K). For temperatures below 220 K the lens freezes but no damage was observed in tests down to 10 K. The transmission of the lens is independent of the operating temperature.

Autofluorescence

The EL-10-30 with LD material is not autofluorescent and can be used for fluorescence microscopy.

Life time

As the EL-10-30 has been released in June 2010, there is limited lifetime information available. However, the lens has passed relevant environmental and accelerated aging tests as outline in the table below.

Test	EL-10-30
Mechanical cycling: 40 million full-range cycles (0 to 300 mA rectangular, at 10 Hz) 5 billion sinusoidal cycles at resonant frequency	Passed
High temperature test: 85±2°C; rel. hum. <6% for 168 hours, non-operational	Passed
Temperature cycling test: -40°C / +85°C for 30 min each, 3 min transition time, 100 cycles	Passed
Damp heat cycling test: 25°C / 55°C at 90-100% relative humidity, 3 hour transition time, 24h per cycle (9h plus transition time each), 18 cycles	Passed
Shock test: 800g for 1ms duration, 5 pulses in each direction (30 pulses in total)	Passed
Solar radiation test: 1120 W per m ² (IEC 60068-2-5), 8 h irradiation & 16 h darkness, 10 cycles	Passed

Table 2: Environmental tests performed on the EL-10-30

Mounting possibilities for the compact EL-10-30



G024503000,
LINOS - Qioptiq



G061042000,
LINOS - Qioptiq



KM200V/M,
Thorlabs



NT57-977,
Edmund Optics



NT64-564,
Edmund Optics



NT03-676,
Edmund Optics

Customization

Optotune's lens technology can be adapted to your needs. The following table provides a range of possible parameters.

Clear aperture (A)	From 2 mm to 55 mm
Range of focal length	From -A to infinity to +A
Response time	As little as 1 ms
Lens shapes	Spherical, from convex to flat to concave, whereby the other side of the lens may be a static free form Cylindrical shapes are possible as well
Cover glasses	BK7, fused silica, sapphire, plastics (PC, PMMA, COC)
Coatings	For cover glasses only

Table 3: Lens parameters that can be customized

Note: Not all criteria can be met at once. For example, larger apertures based on the same EL-10-30 principle are slower and more power consuming. As an alternative, a mechanical design could be used similar to Optotune's ML-20-35 or ML-25-50, which requires no holding power and can easily be motorized.

Ordering information for custom versions of the EL-10-30

For custom versions, please use the following concept for part numbers:

EL-10-30-C-AR-MAT-APP- (F_{\min}/F_{\max})

C = C-mount housing (leave away for compact housing)

AR = VIS : visible broad-band anti-reflection coating (400 – 700 nm)
NIR : near broad-band infrared anti-reflection coating (700 – 1100 nm)
355: narrow-band anti-reflection at 355 nm
1064: narrow-band anti-reflection at 1064 nm
NOC: No coating

MAT = HR: high refraction lens material ($n_D = 1.559$)
LD: low dispersion lens material ($n_D = 1.300$)

APP = MV: Machine vision option: Includes -150 mm offset lens for a total focal tuning range of -600 mm to infinity to +170 mm
LP: Laser processing option: Includes -150 mm offset lens and an optimized membrane for a total focal tuning range of -600 mm to infinity to +400 mm

f_{\min} = minimum focal length

f_{\max} = maximum focal length

Example: EL-10-30-VIS-LD-(+80/+300) refers to a custom electrical tunable lens of 10 mm aperture and 30 mm outer diameter (compact housing) with anti-reflection coating for visible light, low dispersion lens material and a focal tunable range from +80 to +300 mm.