Compact optical design solutions using focus tunable lenses

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ABSTRACT

Several approaches have been demonstrated to build focus tunable lenses. The additional degree of freedom enables the design of elegant, compact optical systems, typically with less mechanics. We present a new range of electrically and mechanically focus tunable lenses of different sizes and tuning ranges and discuss their characteristics. We show how tunable lenses can be used to improve optical design for auto-focus and zoom in terms of size, quality and speed. Furthermore, we present an LED-based spot light with variable illumination angle, which shows optimal performance in terms of spot quality and optical efficiency.

Keywords: Focus tunable lenses, shape-changing polymer lenses, liquid lenses, compact optical design

1. INTRODUCTION

1.1 Motivation

Adaptive optical elements are of great importance in a wide range of industrial, medical and scientific applications [1]. For instance, shape changing diffraction gratings are used as compact optical switches in communication systems and displays [2]. Other examples include liquid crystal displays [3] and spatial light modulators. Additionally, acousto-optic modulators [4] are used in optical microscopes to adjust the intensity of the illumination laser light. Driven by the surge of cameras in mobile phones, a variety of focus tunable lenses are being developed around the globe. Apart from miniaturized cameras, such lenses find countless applications: spot size control in lamps, fast focusing in machine vision or microscopy, more compact ophthalmic equipment or focus control in laser processing to name a few. Furthermore, tunable lens technology has large potential for bio-medical applications in the form of spectacles or even intra-ocular lenses.

1.2 Focus tunable lens principles

There are two principle approaches to focus tunable lenses. The first is based on local changes in refractive index that enable the implementation of a Fresnel lens. These changes can be induced by an electro-optic or acousto-optic effect. The most popular technology for this approach is liquid crystals, with the advantage of low drive voltage, small power dissipation and ease of miniaturization. However, liquid crystals are sensitive to polarization, slow in response due to reordering of molecules and low in optical damage threshold.

The second approach is to control the shape of a lens, which results in better quality, higher tuning range and low polarization dependence. A heavily researched lens technology is based on the electrowetting effect [5]. These so called liquid lenses consist of two liquids with the same density but different refractive indices, typically water and oil. The curvature of the interface can be controlled by applying a voltage to an insulated metal substrate. Advantages of this technology are a compact design, relatively fast response times, low power consumption and inexpensive fabrication. The main drawback is the limited aperture size. As the capillary forces are low it is very difficult to build lenses with apertures over 3mm. In addition, gravity induces a coma when then lens is in upright position (optical axis horizontal) and the density of the two liquids does not match, which is usually the case except for a certain design temperature.

Another category of shape-changing lenses is based on a liquid/membrane principle: An optical liquid is concealed in a container with at least one side being an elastic membrane. A change of pressure in the container causes the membrane to deflect, thus forming a lens. While most of the concepts shown are based on hydraulic or mechanical actuation [6], we present two novel concepts for fast and compact realization of focus tunable lenses, which have led to a variety of commercially available products.

A review of the most common approaches to focus tunable lenses can be found here [7, 8].

1.3 Commercially available focus tunable lenses

To the authors' knowledge, three companies have commercialized a form of focus tunable lenses. The first company to launch a commercial product is Varioptic SA from Lyon, France. Varioptic's lenses implement the electrowetting principle. The focal lengths are voltage controlled (special driver required) and typically range from slightly negative (-200mm) to positive (about 70mm) at aperture sizes of about 2.5mm. Holochip from Albuquerque, USA, offers mechanically controlled shape-changing polymer lens with an aperture of 14.2mm, focusing from 1000mm down to 30mm. In 2010, Optotune AG from Zurich, Switzerland, launched two shape-changing polymer lenses, one being electrical the other mechanical. The EL-10-30 is controlled by current (standard current controller required), has an aperture of 10mm and a focal range of about 120mm down to 15mm (depending on the optical liquid). The ML-20-35 is controlled by turning a ring, has an aperture of 20mm and focal lengths going from -40mm to infinity to +40mm. In 2011 another mechanical lens was launched with an aperture of 25mm and a focal length ranging from infinity down to 23mm.

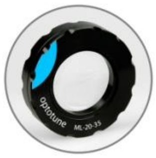
Company	**Varioptic**		**Holochip**	**Optotune**		
Product	Arctic 416 Arctic 316 	Baltic 617 	APL-1050 	EL-10-30 	ML-20-35 	ML-25-50 
Technology	Electrowetting		Shape changing polymer lenses			
Actuation principle	Electrical (voltage controlled)		Mechanical	Electrical (current controlled)	Mechanical	
Aperture [mm]	2.3	2.5	14.2	10	20	25
Outer diameter [mm]	7.75	7.75	45.7	30	35	50
Focal tuning range [mm]	-200 .. ∞ .. +77	-200 .. ∞ .. 67	+1000 .. +30	+120 .. +15	-40 .. ∞ .. +40	∞ .. +23
Maximal NA	0.015	0.019	0.230	0.316	0.243	0.478

Table 1: Comparison of commercially available focus tunable lenses

2. SHAPE-CHANGING POLYMER LENSES

2.1 Why polymers?

Polymers are a very large family of materials, with very diverse properties. We have found a selection of polymers that offer excellent optical and mechanical properties. For membranes, this means that our materials have isotropic optical and mechanical behavior, high elasticity, a large elongation at break, low haze, are transmissive >90% from 240 to 2200nm, non-absorbing (damage thresholds >25kW/cm^2), long-term stable and easy to process. For optical liquids this means that our materials are non-absorbing in a large spectrum, non-yellowing, free of particles, non-toxic and low in viscosity over a large temperature range. We present three liquids with different optical properties (see Table 2). While the high refraction liquid with an n_D of 1.56 allows for applications with very large focal tuning ranges, it is suboptimal for polychromatic imaging due to its high dispersion characteristic. The low dispersion liquid on the other hand only has an n_D of 1.30 but an extremely high Abbe number making it the ideal choice for imaging applications.

	High refraction liquid	**Medium refraction liquid**	**Low dispersion liquid**
Refractive index n_D	1.56	1.46	1.30
Abbe number V	31	55	100
Transmission range [nm]	330-1550	300-2000	240-2500
Toxicity	None	None	None
Yellowing	None	None	None
Applications	Monochromatic applications that require a large tuning range (e.g. lasers)	Illumination systems based on lasers or LEDs	Polychromatic imaging

Table 2: Comparison of three optical liquids

2.2 Shape-changing polymer lens principle

The basic principle of the presented shape-changing polymer lenses is as follows: A thin membrane builds the interface between two chambers each containing an optically clear material, with different refractive index (Figure 1). In the simplest case, one chamber is filled with a liquid, the other with air. The pressure difference between the two chambers defines the deflection of the membrane and with that the radius or the lens.

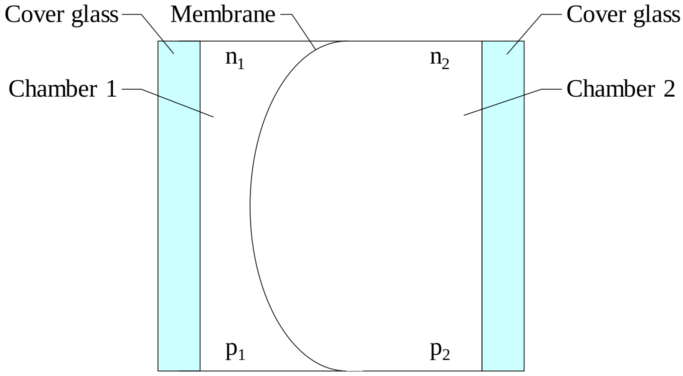


Figure 1: Basic principle of the shape changing polymer lens

The pressure difference can be controlled in many ways: mechanically (e.g. by using a thread ring to push a ring-shaped actuator down onto the chamber, see Figure 2), electromechanically (by using voice coils, piezo or stepper motors to exert the mechanical force, see Figure 3), pneumatically (by pumping liquid into or out of the chamber) or electrostatically (by using the principle of electroactive polymers [9, 10] to change the tension in the membrane).

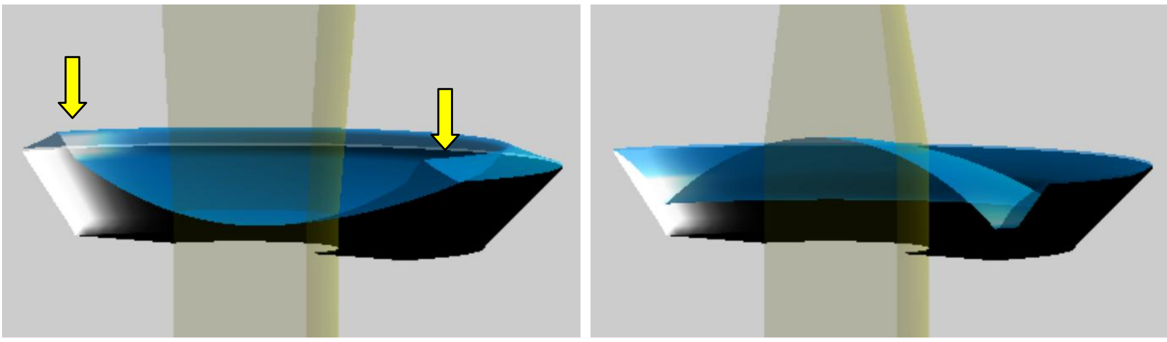


Figure 2: Working principle of the Optotune's ML-20-35, which achieves a lens shape ranging from concave to flat to convex. The ring that forms the lens is pushed towards the container, thus filling the lens with liquid.

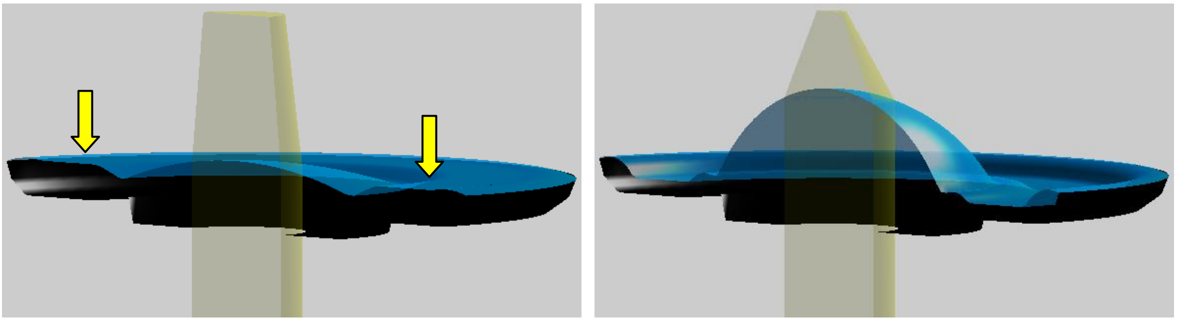


Figure 3: Working principle of the Optotune's EL-10-30. In this case, the lens-shaper ring remains in place relative to the container. The only movement is a ring that pushes down on the membrane with increasing current in the outer part of the lens, thus pumping the liquid into the lens that forms in the center.

This two chamber principle offers many possibilities. Various materials can be used to achieve the desired optical effect. Even a double fluid lens is feasible. The tunable lenses can be shaped from convex to flat to concave and can easily be combined with various types of cover glasses or rigid offset lenses. Figure 2 shows different configurations that are possible.

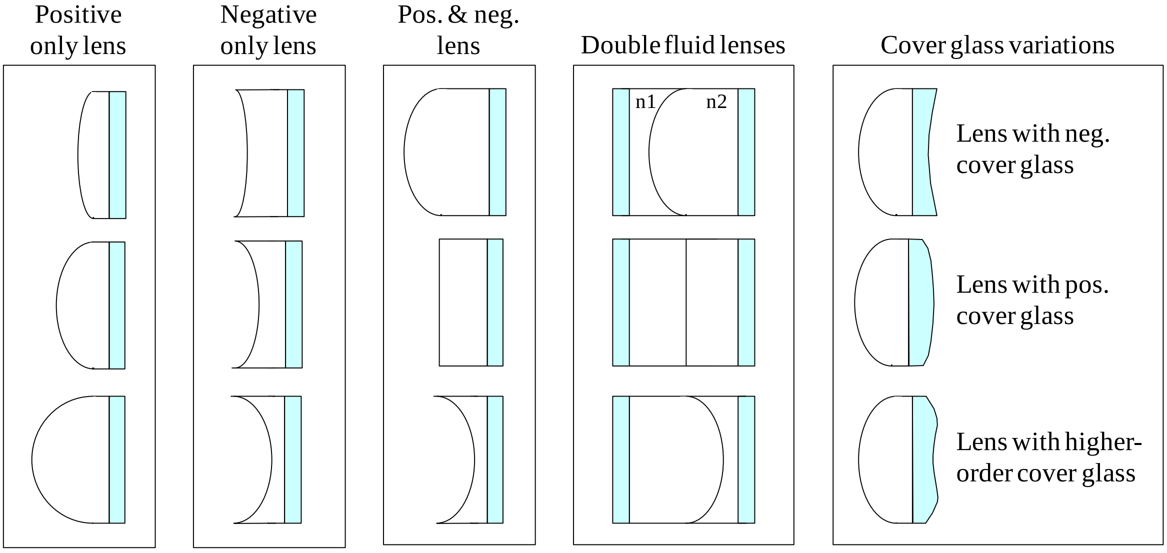


Figure 4: Possible variations of the shape-changing polymer lens

From a number of wavefront and surface measurements, we have found that the lens shape is principally spherical. By changing the mechanical properties of the membrane it is even possible to achieve aspheric lens shapes. Furthermore, by using e.g. a rectangular design, a cylindrical lens can be implemented. In optical simulations the membrane can be modeled as a single surface element, as its influence is negligible due to its minimal and homogenous thickness and the fact that its refractive index is similar to most liquids used.
In general, lens aperture and thickness can be varied from sub-millimeters to several centimeters. The focal tuning range can be designed according to application requirements. However, there is always a trade-off between size, tuning range and response time.

2.3 Pros and Cons of shape-changing polymer lenses

The biggest advantage of shape-changing polymer lenses is the additional degree of freedom offered to optics designers by the focus tunability of the lens. A change in lens radius of several micrometers can have the same optical effect as moving the entire lens several centimeters. Optical systems can thus be designed more compact, oftentimes with less lenses and usually with less or no translational movement. This means that there is no more need for expensive mechanical actuators. Less movement also leads to a more robust design, which can be completely closed so that no dust can enter. Furthermore, the materials employed are all lighter than glass, saving overall weight. Less movement and weight also means less power consumption and that the response time of systems with tunable lenses can be very low, in the order of milliseconds. As can be seen in section 3.1 on auto-focus, using the radius as a degree of freedom can also mean superior optical quality by design. Another advantage becomes obvious during production. The fact that less optical parts are moved combined with the tunability of the radius during operation results in higher yield rates. Finally, the components of the lens can be manufactured at low cost, making this technology suitable for consumer applications.
Some typical downsides of most focus tunable lenses remain. The coma, which is observed with electrowetting liquid lenses, is also an issue for the approach with polymer lenses. While the effect of gravity is negligible when the lens is in horizontal position (optical axis vertical), it is significant when used in upright position (optical axis horizontal). In comparison to the liquid lens the coma is not temperature dependant and is typically smaller, as the membrane has a relatively strong retaining force. Its magnitude depends mostly on size of the lens and mechanical properties of the membrane, but also on density difference of the two materials used. With small lenses of up to 4mm aperture the coma is negligible. At 10mm aperture, the coma term measured is in the range of 0.1 to 0.8 λ RMS (at 525nm), depending on the membrane and liquid used. In general the quality can be improved by using stiffer and thicker membranes. However, that does have a negative impact on tuning range or power consumption. For large lenses (greater than 10mm), best optical quality is achieved by combining stiff membranes with the double-fluid concept, although this is at the expense of focal tuning range.
Depending on the materials used, a thermal expansion can be observed, which has an influence on the lens radius. This can be an issue in open loop systems. As this effect is systematic, it is consistent over the life-time of a lens and can usually be handled by sensing the temperature and using look-up tables.

3. COMPACT OPTICAL DESIGN SOLUTIONS

In this section the advantages of focus tunable lenses are discussed from an optical design perspective. Instead of presenting complex multi-lens designs we demonstrate some key principles that are easy to understand and replicate.

3.1 Auto-focus

Traditionally, focusing on objects at different distances is solved by moving a single lens or a group of lenses along the optical axis. A simple example where this is done with one lens is shown in Figure 5. In A) the system is focused at infinity and exhibits a relatively good resolution with an MTF30 value of 96 line pairs per millimeter. In B) the object distance is reduced to 100mm and no re-focusing is performed. The result is a disastrous drop in resolution. In C) the lens is axially repositioned by 1.36mm to re-focus, resulting in an MTF30 of 38lp/mm, which is still a large drop in resolution. In D) the re-focusing is achieved by tuning the shape of the lens (central deflection is increased by 0.04mm). The resulting MTF looks much better with the MTF30 at 62lp/mm.
Apart from the better resolution it can be noted that the movement for tuning the lens in D) is 34 times smaller than the axial repositioning in C). In consequence it is reasonable to assume that an autofocus system with tunable lenses can be

designed with significantly less total height and that less actuation is needed. The latter also means that focusing can be performed faster and with less power consumption.
Another benefit of tunable lenses becomes apparent in E). If the object distance is further decreased down to 50mm, the system can easily be re-focused by deflecting the lens another 0.04mm. The resulting MTF curve is still significantly better than in C) with an MTF30 of 46lp/mm. In this example, it was actually not possible to focus on 50mm by axial movement as the lens would have crossed the aperture stop. Focus tunable lenses are thus oftentimes the only means to design systems with very large focus ranges.

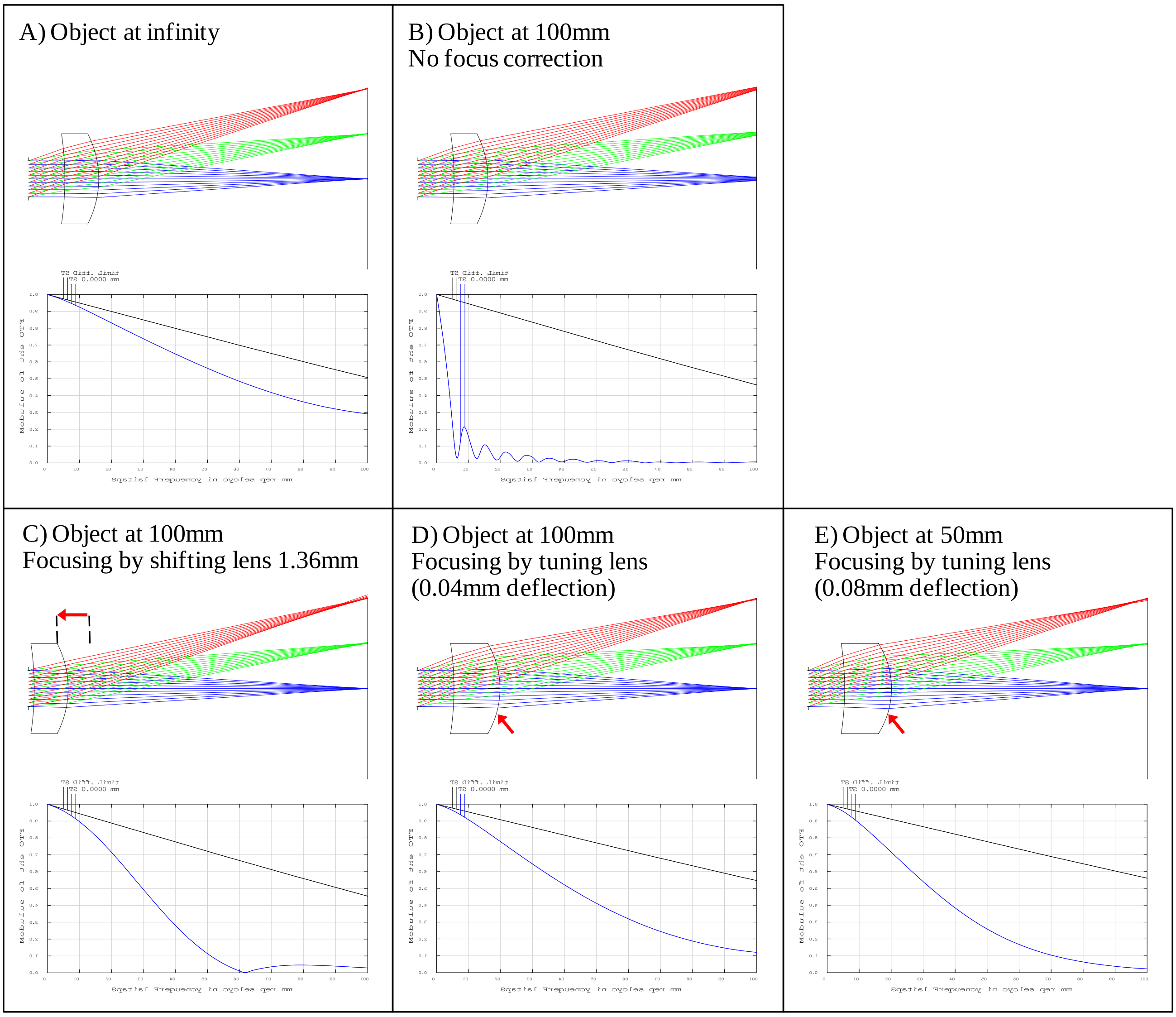


Figure 5: Comparison of focusing by translation versus tuning of a lens. For better readability only the zero-field is illustrated in the MTF plots, as the effect is very similar for fields on the sensor.

In microscopy axial focusing of several hundred micrometers can be achieved using focus tunable lenses. Traditionally, this would require moving the specimen or the objective with precision piezo stages. By including focus tunable lenses in the optical pathway, focus control becomes movement-free and faster. Optotune's EL-10-30 has proven to be applicable for several types of microscopy including wide-field microscopy, confocal microscopy and two-photon microscopy [11]. An example optical setup for the latter is depicted in Figure 6.

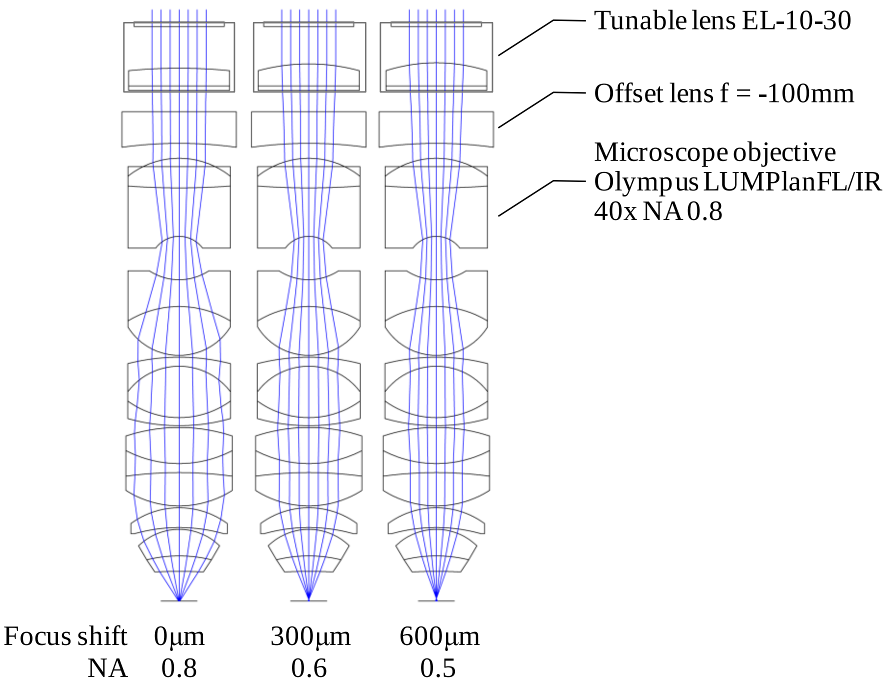


Figure 6: Example of axial focusing in two-photon microscopy using Optotune's EL-10-30, a concave offset lens and 40x NA 0.8 microscope objective [12]

3.2 Optical zoom

In the previous example on auto-focus, we have seen that focus tunable lenses can significantly reduce the overall height of an optical module. This advantage becomes even more apparent for zoom designs, where usually two or more lenses or lens groups are axially repositioned. A very basic solution is shown in Figure 7. Two lenses are used in this example that both change their shape from convex to concave. The backsides of the two lenses are assumed to be rigid and are used to optimize the optical performance of the module across three zoom states. This would correspond to using lens-shaped cover glasses with a refractive index identical to the optical liquid. All lens surfaces are spherical.

The module was designed to achieve a zoom factor of 3.27 (semi-field-of-view variable from 10° to 30°). Assuming the image sensor to be 4mm in diagonal (1/4" sensor), the total height of the model results in 14mm. That height could be further reduced by adding additional lenses to the system and running respective optimizations.

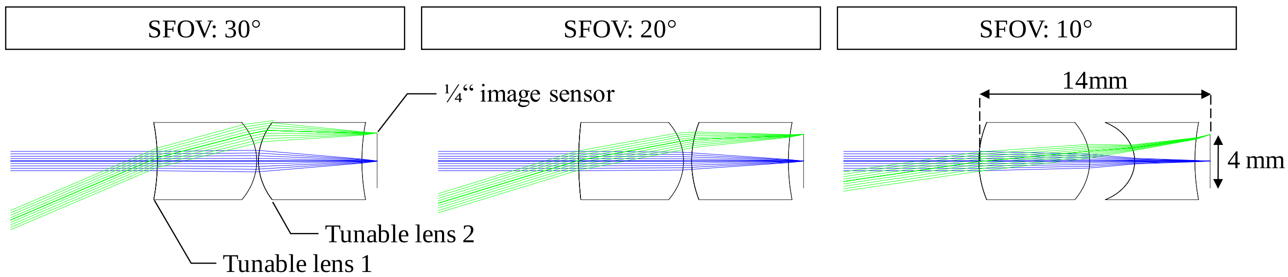


Figure 7: Example of a compact zoom design using two focus tunable lenses. With semi-field-of-view angles going from 30° in wide angle to 10° in tele mode, a zoom factor of 3.27 is achieved.

3.3 Variable spot sizes in illumination

Apart from imaging applications focus tunable lenses prove to be very useful for illumination purposes. As large tuning ranges and high optical powers are required, shape-changing condenser lenses are particularly suited. A basic application presented here is a spot light with a variable beam angle going from “flood” to “spot” mode. The design includes an LED, secondary optics (total-internal-reflection lens), a shape-changing condenser lens and a protective cover glass (see Figure 8). The LED and the secondary optics together define the maximum beam angle of the spotlight, which is achieved in the planer state of the tunable lens when the light passes through without any deflections. By tuning the condenser lens to a convex shape the light is focused to a smaller spot size.

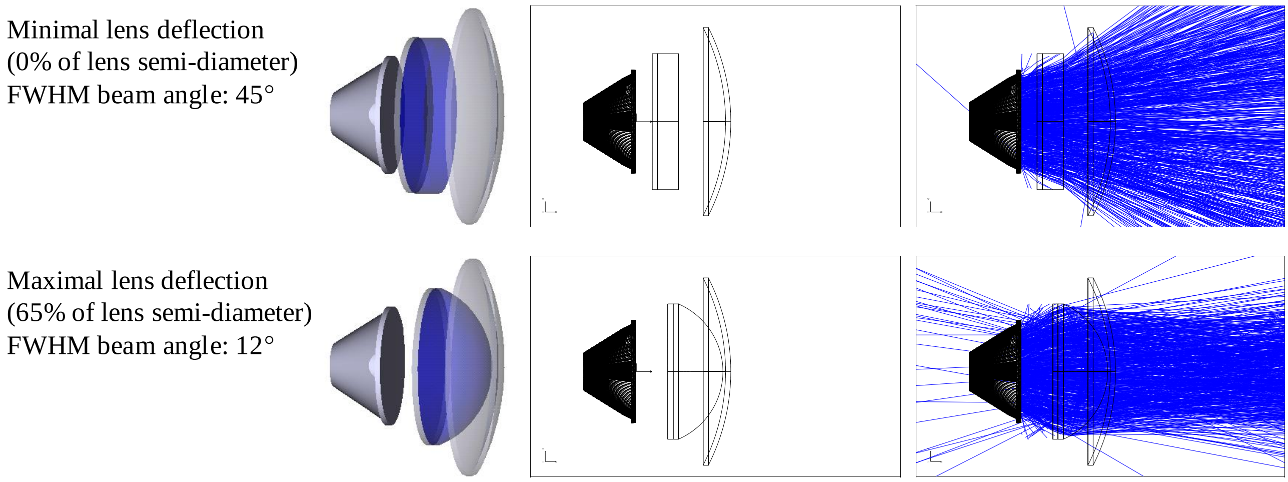


Figure 8: Example of adaptive illumination using Optotune’s ML-25-50 Lumilens

The components used in this example are a Cree MC-E LED, a Carclo 10196 "Frosted Wide" TIR-lens and Optotune’s ML-25-50 Lumilens. The resulting beam angles range from 45° FWHM (full width half maximum) down to 12° FWHM. The tuning range could be even further increased if the tunable lens was to start in a concave state, which is possible but would require a more complex mechanical design of the lens.

A change in beam angle could also be achieved by axial movement of lenses. However, there are several advantages of the approach with a tunable lens. As the lens is not shifted away from the light source no light is lost, which results in high optical efficiency over all tuning states. The spot quality also remains consistent over the entire tuning range, unlike the frequent appearance of intensity rings when lenses are shifted. Also, the low-dispersion materials ensure that no color errors occur. Finally, the optical design remains comparably compact.

While most lighting situations require a diffuse spot, it is sometimes required to have a homogenously lit up spot with a specific delimiting shape, e.g. a trapezoid for perspective illumination of a painting in a museum. In such cases, an intermediate mask is imaged by projection optics. The same principle applies to gobo projectors, where the mask contains a slide e.g. of a company logo. To vary the size of such a projection zoom optics are required that include several lenses. Again, focus tunable lenses can help reduce the size and increase the efficiency of such optics. The basic design for such systems follows the design discussed above in section 3.2.

4. CONCLUSION

Focus tunable lens principles have been researched for a long time and some have successfully found their way into commercial applications in the past few years, electrowetting lenses in particular. However, the range of applications is still limited, mainly due to the constraint in aperture size to about 2.5mm. The introduction of a variety of shape-changing polymer lenses opens up numerous new possibilities. Especially zoom applications benefit from the increase in focal tuning range and illumination applications benefit from large aperture sizes of several centimeters. The high quality of the polymer materials used even allow to enter applications, which have been reserved for highest quality glass lenses like high-power laser processing in UV or near infrared. In consequence, we expect focus tunable lenses to grow in importance, especially in designs where versatility, compactness and speed matter.

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REFERENCES

[1] U. Wittrock, editor. “Adaptive optics for industry and medicine”. Springer (2005).
[2] O. Solgaard, F. S. A. Sandejas, and D. M. Bloom. “Deformable grating optical modulator”. Opt. Lett., 17(9):668-690 (May 1992).
[3] G. W. Gray and S. N. Kelly. “Liquid crystals for twisted nematic display devices”. J. Mater. Chem., 9(9):2037-2050 (1999).
[4] A. Korpel. “Acoust-optics”. Academic Press, 2nd edition, (1988).
[5] L. Saurei, J. Peseux, F. Laune and B. Berge. “Tunable liquid lens based on electrowetting technology: principles, properties and applications”. 10th Ann. Micro-optics Conf. (Sept. 2004).
[6] H. Ren, D. Fox, P. A. Anderson, B. Wu, and S.-T. Wu. “Tunable-focus liquid lens controlled using a servo motor”. Optics Express, Vol. 14, No. 18 (Sept. 2006).
[7] A. Wilson, editor. “Tunable Optics”. www.vision-systems.com/articles/2010/07/Tunable_Optics.html (2010).
[8] H. Zappe, editor. “Fundamentals of Micro-Optics”. Cambridge University Press (2010).
[9] Y. Bar-Cohen, editor. “Electroactive polymer (EAP) actuators as artificial muscles”. SPIE press, 2nd edition (2004).
[10] T. Mirfakhrain, J. D. W. Madden, and R. H. Baughman. “Polymer artificial muscles”. Materials Today, 10(4):30-38 (April 2007).
[11] B. F. Grewe, F. F. Voigt, M. van't Hoff, F. Helmchen, “Fast two-layer two-photon imaging of neuronal cell populations using an electrically tunable lens.” Biomedical Optics Express, Vol. 2, Issue 7, pp. 2035-2046 (2011).
[12] A. Katsuyuki, “Embodiment 1” Japanese Patent 8–292374 (Nov. 5, 1996).