On the possibility of intraocular adaptive optics

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Abstract: We consider the technical possibility of an adaptive contact lens and an adaptive eye lens implant based on the modal liquid-crystal wavefront corrector, aimed to correct the accommodation loss and higher-order aberrations of the human eye. Our first demonstrator with 5 mm optical aperture is capable of changing the focusing power in the range of 0 to +3 diopters and can be controlled via a wireless capacitive link. These properties make the corrector potentially suitable for implantation into the human eye or for use as an adaptive contact lens. We also discuss possible feedback strategies, aimed to improve visual acuity and to achieve supernormal vision with implantable adaptive optics.

OCIS codes: (010.1080) Adaptive optics; (170.4460) Ophthalmic optics; (330.1070) Acuity.

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1. Introduction

It was shown recently that the aberrations of the human eye can significantly contribute to the loss of the visual acuity [1]. The resolution of the retina is higher than the optical resolving power of the human eye [2]. Traditional correction with spectacles is useful for only two aberrations – defocus and astigmatism [3, 4]. To facilitate the correction of higher-order aberrations, the corrector should be optically conjugated to the eye pupil. To achieve such a conjugation, an imaging optical system is used to make the image of the corrector co-incident with the eye. Breadboard adaptive optical setups, based on this principle, were successfully built to demonstrate the feasibility of high-order correction [5, 6, 7] and the conclusions were that the resolution of the eye can be improved over the natural limit, leading to "supernormal" vision.

The breadboard setups realized so far are applicable only for clinical and laboratory use and cannot be converted into wearable devices due to their bulkiness and complexity.

Another ophthalmic problem that can be corrected with adaptive optics is the age-related or post-surgery loss of accommodation. Attempts were made to develop a corrector for presbyopia [8] with little practical success.

Here we present the first results of our experiments with wireless control of liquid-crystal wavefront corrector, proving the technical feasibility of dynamic correction of human-eye aberrations by placing the wavefront corrector directly into the pupil of the human eye. We consider two possibilities:

- A non-invasive way, which suggests integration of the wavefront corrector into a contact lens;
- the invasive approach, which suggests implantation of the wavefront corrector directly into the human eye (see Fig. 1).

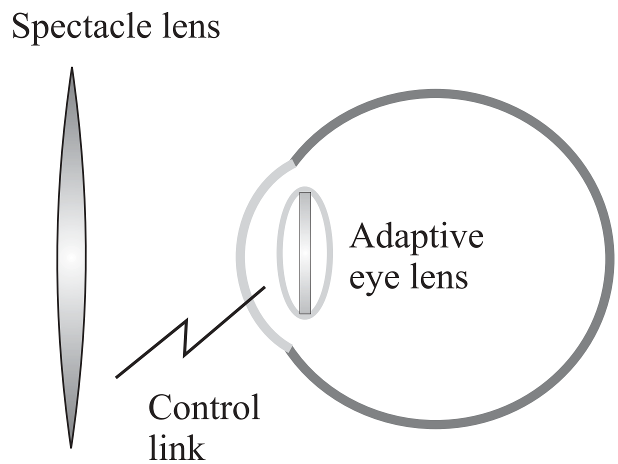

Fig. 1. Implantable adaptive eye lens

2. Liquid-crystal wavefront correctors

Liquid-crystal (LC) modal lenses and multichannel wavefront correctors, demonstrated recently [9, 10, 11], are potentially well suited for wavefront correction in the human eye because of their small size – several millimeters in diameter, with the thickness limited basically by the thickness of the LC layer which is 10 to 50 μm, low power consumption – of the order of tens of microwatts, low control voltage – in the range of 0 to 10V and a wide range of optical power: up to $\sim$3 D - which, translated into the accommodation depth of the human eye, is from infinity to $\sim$30 cm.

The modal liquid-crystal lens [9] consists of two electrodes with an oriented layer of nematic LC between them. The top electrode is highly conductive, while the bottom electrode is formed by a conductive ring deposited over a highly resistive 1-10 MΩ/square electrode. When a bipolar *ac* voltage is applied between the top conductive electrode and the bottom conductive ring, the radial voltage distribution inside the ring follows a smooth, parabola-like function with its minimum co-incident with the ring center. The amplitude and the shape of the function depend on the amplitude and the spectral composition of the driver signal. Since the orientation of the LC molecules follows the voltage distribution, a lens-like device is formed. The amplitude and spectral composition of applied unipolar *ac* voltage can be used to control the optical power and radial aberrations of the modal LC lens [12] - see Fig. 2 for an example of defocus and spherical aberration, formed by the same lens at different control parameters. Azimuthal components can be realized by splitting the annular control ring into sectors with independent control signal applied to each sector.

Although technically challenging, all optical and electrical parts of the liquid-crystal modal corrector, including wireless control, can be integrated between two thin sheets

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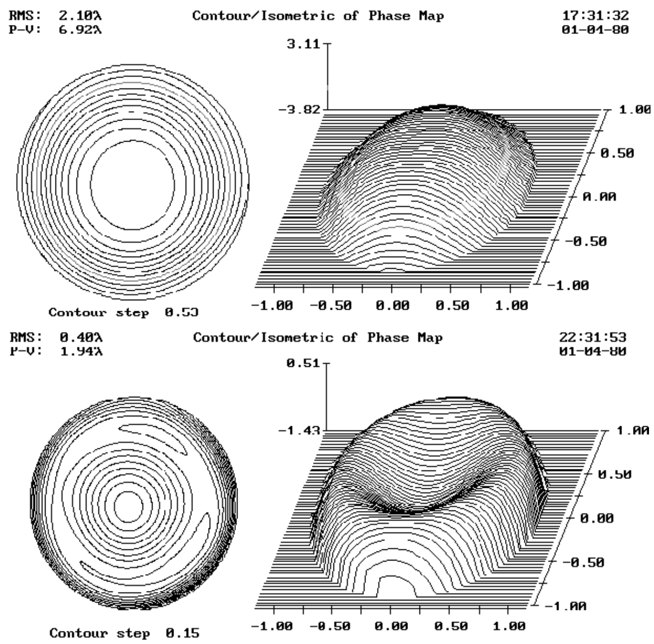

Fig. 2. Defocus (V = 3.64 V, F= 2.44 kHz) and spherical aberration (V=2.0 V, F=3 kHz) formed with a 10 mm LC lens.

of transparent plastic with a total thickness of the order of tens of micrometers using a ”Silicon-on-anything” technology [13].

In case the LC lens is implanted into the human eye or used as a contact lens, it should satisfy the following requirements:

- Both the LC material and the lens optics should be biologically compatible. Not all LC materials satisfy these requirements [14]. Merck’s data sheets declare liquid-crystal materials ”not acutely toxic”, moreover according to tests conducted on 224 liquid-crystal substances [15], 215 compounds did not have any acute toxic potential. Eye irritation tests performed with 14 LC compounds proved all 14 compounds to be non-irritant.
- The corrector should combine adaptive optics with the receiving of external control signals. In addition, some kind of feedback – either psychophysical or objective – should be present to generate the control signals. In the simplest case, manual control of the focusing power and spherical aberration of the corrector can be implemented.
- While the implantable lens dimensions should not exceed 4 mm in thickness and 9 mm in diameter - about the size of the eye lens [16], the adaptive contact lens thickness should be limited to several tens of micrometers – the typical thickness of an ordinary soft contact lens.
- A simple LC lens acts only on one polarization state of light. There are two ways to use the lens with randomly polarized light: to combine it with a linear polarizer - resulting in a light loss of 50%, or to combine two lenses acting on orthogonal polarization states.

3. Wireless control

The adaptive lenses, described above can easily be fabricated to match the size of the human eye lens. However, it is much more difficult to organize the wireless control, as, we believe, no wires can be used in the human eye and no battery can be embedded into the lens.

The wireless link to the intra-ocular lens should supply the necessary power and at the same time it should carry the information about the optical parameters of the corrector, such as the optical power and the aberration terms. In the case of an adaptive lens with an analog *ac* drive, the focusing power will correspond to the amplitude of the signal, while the radial aberrations can be controlled by the signal spectrum [12].

The typical power required to drive the lens is in the range of 50 μW to 1 mW (see Fig. 3), depending on the control frequency and the parameters of the coating and the liquid-crystal. This power should be transferred to the lens through the wireless link.

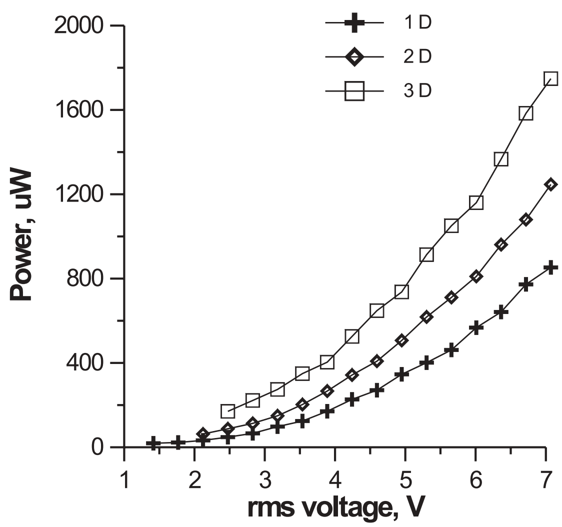

Fig. 3. Experimentally measured reactive power required to drive the LC lens as a function of the driving voltage and the focusing power. Since the lens is a reactive load, the active power dissipated in the lens is considerably smaller than shown in this graph.

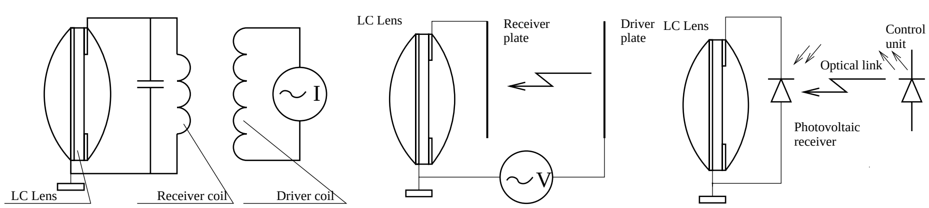

Fig. 4. Schematic of inductive (left), capacitive (middle) and optical (right) control of an implantable LC lens.

The following wireless link principles should be considered:

- An inductive link using linked coils – see Fig. 4 left. The transmitter coil is integrated into the frame of the spectacles, while the receiver coil is integrated in the adaptive LC lens, around the optically active area – see 3D model in Fig. 5.

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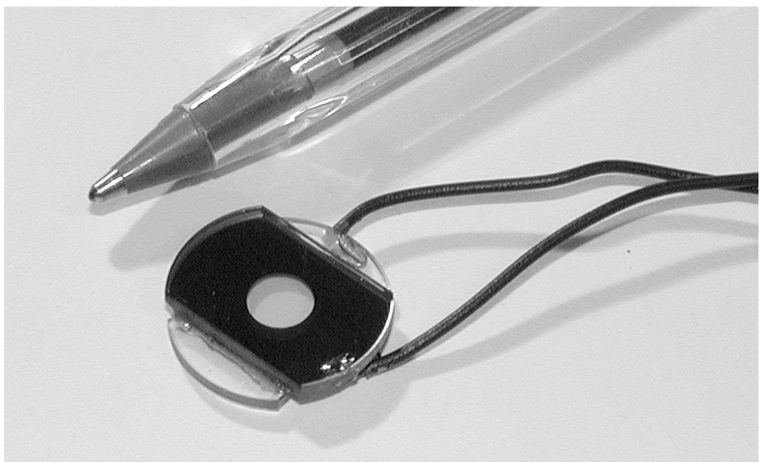
- Electrostatic link via linked capacitors – see Fig. 4 middle. The field inside the external capacitor (formed for instance between the conductive coating on the spectacles and the active plate of the LC lens) is driving the LC lens.
- Optical IR link to the photovoltaic receiver integrated into the LC lens – see Fig. 4 right.
- Finally, feasibility research should be done to control the lens using the bio-electrical signals that normally control the natural accommodation of the eye.

4. Experimental proof of concept

We have fabricated a number of adaptive LC lenses with a diameter of 15 mm and thickness of 4 mm, with a clear light aperture of 5mm and the LC layer thickness of 25 and 50 μm (see Fig. 5). These dimensions were dictated by the ease of manufacture. Nevertheless, the optical parameters of the lens are close to those required for intra-ocular application; the main difference is the overall size and the lack of integrated control electronics and a wireless link.



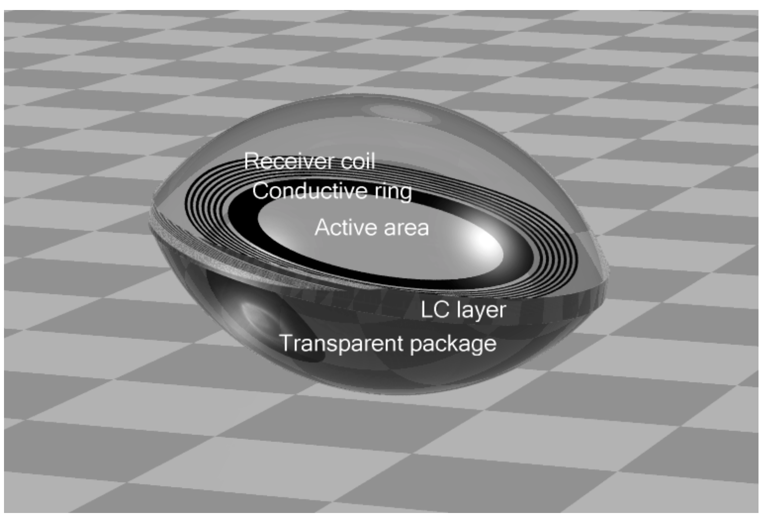


Fig. 5. Adaptive LC lens fabricated for experiment with wireless control (top) and 3D model of a wireless implantable LC corrector with integrated receiver coil for remote control (bottom).

Our first experiments with an inductive link (for which we used two external coils to control the LC lens) resulted in a too low voltage on the LC layer (of the order of tens of millivolts). This voltage can be increased by a matched capacitor connected in parallel to the receiver coil and by increasing the mutual magnetic flux of the receiver and transmitter coils.

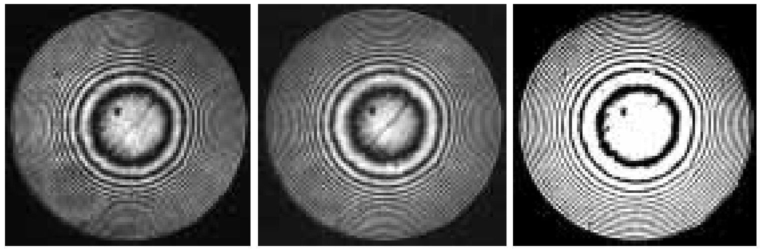


Fig. 6. Interferometric patterns obtained experimentally for green (543 nm), yellow (594 nm) and red (632 nm) colors (left to right) using wireless capacitive control of the adaptive LC lens.

Experiments with the capacitive link (two plates with an area of 3x3 cm each at a distance of 1 to 10 mm) resulted in reliable control of the optical power in the whole range of the adaptive LC lens (see Fig. 6). The control voltage applied to the driver plate reached 45 V and the driver current was of the order of 10^{-5} to $5 \cdot 10^{-4}$ A. As in the previous case, the efficiency can be improved by using a resonant LC-contour to increase the control sensitivity. Figure 7 gives an impression of the combination of the control voltage and frequency that should be applied to the LC lens to control only defocus. Deviations from these values will result in additional radial aberrations, that can be also calibrated and used to correct the aberrations of the eye.

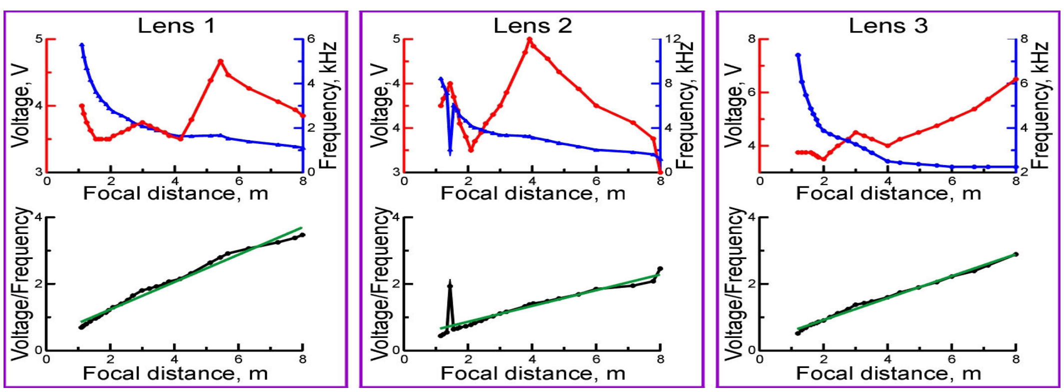


Fig. 7. Voltage-frequency calibration curves for three different LC lenses.

As for the photo-voltaic control, the main problem is the biological compatibility of such a control with the human eye. In fact, we need to have an optical source with a power of the order of 50μW to 1 mW, permanently shining into the area around the eye pupil. Though the wavelength can be in the invisible range, the long-term effect of such an exposure can be negative, though the situation can be improved by optimization of the configuration of the optical link.

5. Compensation of chromatic aberrations

The chromatic aberration of the human eye can reach $\sim$0.75 D in the wavelength range 400 to 650 nm with longer focus corresponding to a shorter wavelength [17, 18]. Liquid-crystal lenses feature chromatic aberration of the opposite sign [19], with shorter focal length corresponding to the shorter wavelength. This is illustrated in Fig. 8 by computer reconstruction of the interferograms in Fig. 6.

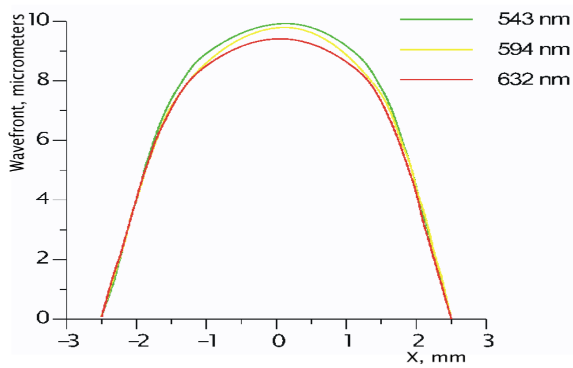


Fig. 8. Interferograms in Fig. 6, reconstructed for three color components. Chromatic focal lengths of the LC lens evaluated from these data are ∼26 cm for green, ∼30 cm for yellow and ∼32 cm for red light.

An adaptive LC lens will naturally compensate for the chromatic aberration of the human eye.

6. Control algorithms

To our knowledge there is no experience with control of intra-ocular adaptive optics. Authors suggest that low-order aberrations, such as defocus and astigmatism, can be corrected dynamically by a psycho-physical feedback or even manual adjustment of the focusing power, spherical aberration and astigmatism. Higher-order aberrations should be compensated dynamically by the means of automatic feedback with the wavefront sensor embedded, for instance, in a wireless controller or by using the neural bioelectric signals that are generated by the human brain.

7. Conclusions

As published recently [2, 5, 6] the resolution of the human eye can be improved by correcting the eye lens aberrations. Compensation of high-order aberrations is possible only if the corrector is optically conjugated with the eye lens.

We propose to use the modal LC corrector as an adaptive contact lens or as an adaptive eye lens implant. It solves the problem of optical conjugation and allows for correction of aberrations directly inside the eye.

We suggested three ways of wireless control of the adaptive contact lens or lens implant: an inductive link, an electrostatic link and an optical link. In our experiments we fabricated a 5 mm LC contact lens and demonstrated wireless electrostatic control in the range of ∼3 D, corresponding to an accommodation depth from infinity to ∼30 cm.

Based on the results of our preliminary experiments, it seems possible to develop a wireless-controlled adaptive contact lens or eye lens implant for correction of accommodation loss and also, in the future, multichannel correctors for dynamic correction of high-order aberrations of the human eye.

8. Acknowledgements

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