Eye (2010) 24, 1716–1723

www.nature.com/eye

LABORATORY STUDY

A 'living' prosthetic iris

J Lapointe[1,2], J-F Durette[3], A Harhira[1,2], A Shaat[4], PR Boulos[5] and R Kashyap[1,2]

[1]Department of Engineering Physics, Advanced Photonics Concepts Laboratory, Ecole Polytechnique de Montreal, Montreal, Quebec, Canada

[2]Department of Electrical Engineering, Centre of Research in Electronics and Radiofrequency, Ecole Polytechnique de Montreal, Montreal, Quebec, Canada

[3]Oculo-Plastik Inc., Montréal, Québec, Canada

[4]Department of Ophthalmology, Faculty of Medicine, Ain Shams University Hospital, Cairo, Egypt

[5]Department of Ophthalmology, Faculty of Medicine, Hôpital Maisonneuve-Rosemont, University of Montreal, Montreal, Quebec, Canada

Correspondence: J Lapointe, Department of Engineering Physics, Advanced Photonics Concepts Laboratory, Ecole Polytechnique de Montreal C.P. 6079, Succ. Centre-ville, Montreal, Quebec H3C 3A7, Canada.
Tel: +1 514 340 4711;
Fax: +1 514 340 3218.
E-mail: jerome-2.lapointe@polymtl.ca

Received: 18 May 2010
Accepted in revised form: 22 July 2010
Published online: 17 September 2010

Abstract

Aim To design and demonstrate dynamic pupils, which react to light for use with ocular prostheses.
Methods The realism of ocular prostheses is limited by the immobility of the pupil. Our solution is to use a liquid crystal display (LCD) in the prosthesis to vary the pupil size as a function of the ambient light. Several liquid crystal cells were fabricated and tested for survivability through the ocular prosthesis manufacturing process. The dynamic pupil is controlled by a novel and entirely autonomous, self-powered passive electronic circuit using a solar cell, matching the minimum diameter of the pupil.
Results The first LCD surviving the rugged conditions of the ocular prosthesis manufacturing steps and an entirely passive circuit controlling the pupil have been demonstrated for the first time to our knowledge. A design for a complete prosthesis with a dynamic pupil has been proposed. Finally, a standard device for the mass production of ocular prostheses is presented.
Conclusion We have shown that a practical solution for an autonomous self-powered dynamic pupil is possible, given the constraints of size, fabrication process, weight, cost and manufacturability on a mass scale. We envision that the LCD could be mass produced, and only the final steps for the integration of the iris matched to a patient would be necessary before assembly using standard processing steps for the production of the prosthesis. Using a clinical trial, we hope to demonstrate that the dynamic pupil will have a positive impact on the quality of life of patients.

Eye (2010) **24,** 1716–1723; doi:10.1038/eye.2010.128; published online 17 September 2010

Keywords: ocular prosthesis; prosthetic eye; iris; pupil; LC; PMMA

Introduction

The realism of an ocular prosthesis is limited by the inability of the artificial pupil to react to light. This has a negative impact on patients who have received a single prosthetic implant to replace an eye. A good proposed solution to the problem is to use liquid crystal display (LCD) technology as a color spatial light modulator to control the pupil size.[1] Up to now, very few reports have been made but no successful result has been put forward.[2] The principal problem is that the LCD does not survive the rugged conditions of the ocular prosthesis manufacturing process.

This study demonstrates the first LCD to our knowledge surviving the ocular prosthetic manufacturing steps and an entirely passive circuit to control the pupil diameter. A few micrometers square integrated circuit chip, including the passive circuit and a solar cell (SC), is proposed, with the LC cell to constitute a standard device for the mass production of ocular prostheses. The integrated chip, which controls the pupil size through the LC cell, is autonomous and powered by the SC alone. Future work for a complete prosthesis with a dynamic pupil is also discussed.

Materials and methods

There is a requirement in ophthalmology for a prosthetic iris that is self-accommodating, to improve the quality of life of patients who have lost an eye. The present work addresses this need by exploring a solution on the basis of the LC displays. The proposed solution is to use a small LCD, positioned over an iris image, in which ring-shaped pixels will appear black or transparent depending on the ambient light, to simulate the dynamic pupil.

Principle of a liquid crystal (LC) cell

An LC cell, see Figure 1, is made of two indium tin oxide (ITO)-coated (c) glass plates (b) with the LC (e) between the two plates. In Figure 1a,

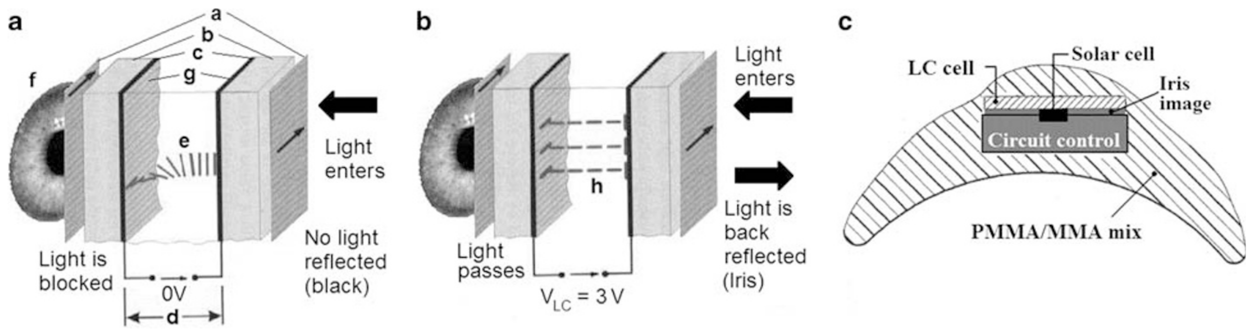

Figure 1 Principle of operation of the LC cell. (a) Without potential applied, the image of the iris appears black. (b) With potential applied, the image of the iris is seen in reflection. (c) Section of the ocular prosthesis with proposed LCD dynamic iris.

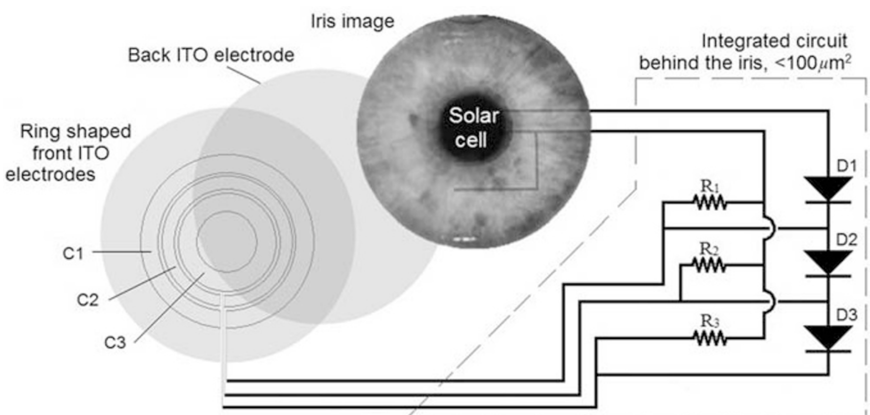

Figure 2 Schematic of the electrical operating principle of the dynamic pupil with the passive voltage selector circuit. Each ring-shaped LC pixel is a capacitor.[3]

light enters the LC cell from the right and is horizontally polarized by the polarizer (a). The light passes the glass substrate (b), the transparent ITO electrode (c), and the orientation layer (g). The rod-like LC molecules (e) have the property to align themselves together and using the transparent orientation layer (g), make the helicoidal shape (e) shown in the figure. Without the potential applied, when the light passes through the LC medium, the polarized light rotates by 90° to become vertically polarized because of the birefringence in the LC. The sequence layers on the rear glass plate are identical to the entry surfaces, and vertically polarized light is blocked by the second polarizer, which allows only the horizontally polarized light through. The image of the iris is placed in contact with the rear exit glass plate. No light is reflected and, therefore, the image of the iris appears black.

In Figure 1b, under an applied electric field, the positive dielectric anisotropy LC (h) aligns with the direction of the electric field, therefore, leaves the polarization of the light unchanged and the light passes through the LC cell. The iris image is thus reflected, passes a second time through the LC cell and is, therefore, seen in reflection. Using this concept, the passage of the light may be controlled through the LC cell.

Design of the dynamic pupil

To simulate a dynamic pupil, ITO electrodes are designed to be concentric annular in shape. Figure 1c shows a schematic of the dynamic pupil in an ocular prosthesis using our design of the LC cell. In our design, we add a specially designed SC, so that dynamic control of the pupil can be implemented. The silicon (or thin-film, polymer, or other) SC, lies behind the iris and has a diameter of the minimum opening of the pupil. The intensity of the ambient light is detected by the SC, which generates the potential needed to switch the ring-shaped LC pixels. In order that the light level may be detected, a simple and novel level selector circuit is added for switching the different ring-shaped LC pixels, as shown in Figure 2, which are controlled on the basis of the level of the ambient light.

To operate the dynamic pupil, the LC needs a minimum electric field E_{min} to obtain a good molecular alignment. The potential required is then $V = E_{min}d$, where d is the distance between the two LCD electrodes. To minimize the potential and the cost of the ocular prosthesis, a minimum distance, about $d_{\min} = 3.2\,\mu$m,[4] must be chosen for the LC used in our experiments. Furthermore, the static LCD requires almost no current, and a potential at the minimum distance $d_{\min}$ is approximately 2–3 V. The current is determined by the leakage through the high resistivity LC cell and the speed of switch-on. As both these can be very low, the power requirements are almost negligible, requiring no power supply. Thus it is important to have a control mechanism that is passive and consumes a minimum of power to control the pupil. Using a novel passive circuit connected to the concentric ring electrodes and the SC with several discrete sections in series, each with a potential of 0.7 V,[5] the correct potential can be easily achieved to operate the LCD,[6] making the dynamic pupil autonomous. An implanted rechargeable battery is not desirable, as it requires periodic replacement owing to limited lifetimes, adds to cost, and increases the mass, which poses other problems of prosthesis droop. Thus our system solves important issues by reducing not only the cost and long-term management, but also the stringent weight requirements.

The passive electronic circuit

Figure 2 shows the schematic of the components required for the electrical operating principle of the dynamic pupil. The ITO electrodes are transparent. When it is dark, the potential is also low and the LC cell is not operated at all, and thus the entire LC cell is left in the OFF state, by using parallel polarizers, and is therefore seen as black. The light is blocked so that the pupil appears large.

Each ring-shaped electrode acts similar to a capacitor (C1, C2, and C3). An electrode will let the light from the iris image to pass through it when the applied potential is around 3 V or more. A diode drops the potential by around 0.5 V depending of the diode type and the current. To operate the largest diameter electrode, the interconnected SCs must generate 3V + 0.5 V = 3.5 V, which lets the light pass through. With more light, the SC must generate $3 + 0.5 \times$ nV, to operate the nth ring electrode to make the pupil appear smaller. Without the resistance connected, there is no current flow as the LC electrodes operate as capacitors. With a current close to zero, the diode potential drop is also close to zero and all the pixels remain in the ON state for practically the same illumination; however, with the resistors in place, the potential drop increases sequentially operating the electrodes in sequence, with increasing illumination.

This circuit is very flexible and can be adjusted for most pupils that react differently under illumination. The number of interconnected SCs, the diode type and the number of diodes may be changed simply to simulate a patient's pupil. Figure 3 presents a simulation of this circuit. ($C_1 = C_2 = C_3 = 1.1$ nF, $R_1 = R_2 = R_3 = 10\,k\Omega$, and $V_D = 0.5$ V)

The adjustability of the pupil is determined by band-gap of the diode. However, the resistors can be changed

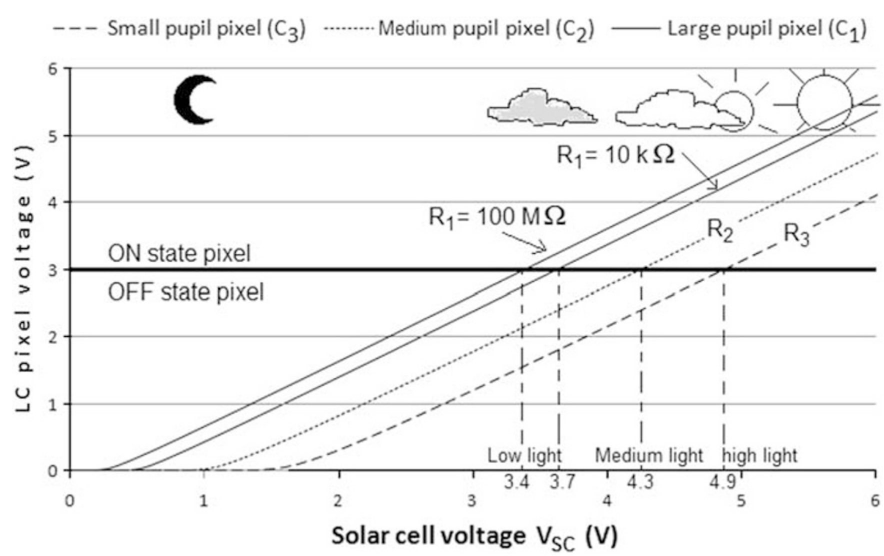

Figure 3 Simulation of the passive circuit. Each line shows the potential applied to each LC pixel as a function of illumination of the SC. The long dashed line is the potential across a LC pixel in series with three diodes, which is in the ON state under a high light ambient ($V_{SC} = 4.9$ V). Small dashed line: two diodes, ON at medium light ($V_{SC} = 4.3$ V). Solid line: one diode, ON at lower light ($V_{SC} = 3.7$ V for $R_1 = 10\,k\Omega$. $V_{SC} = 3.4$ V if $R_1 = 100\,M\Omega$).

to fine tune the output voltage. For example, if the patient's pupil reacts under lower light, one can increase the resistor in parallel with the larger pupil pixel ($R_1 = 100\,M\Omega$, requiring a current of $<50\,nA$, easily obtained from small SCs). The simulation in Figure 3 shows that the large pupil pixel curve shifts to the left.

The high voltage SC

Under a constant illumination on its exposed surface, a SC generates a constant power $P = IV$. As our application does not need substantial current I, the SC can be modified to maximize the voltage V. Figure 4 (Right) shows the design of such SC.

The SC is sectioned and by interconnecting them in series, the voltage is multiplied. This concept is well known and can generate higher voltages[5,6] than the single cell, and than the device needs with an SC size equal to the minimum diameter of the pupil ($\sim$3 mm). Using this concept, the device can be self-powered and autonomous.

Will the SC generate enough current to operate the device? The answer is yes. First, in the dark it does not need any illumination and the pixels remain in the OFF state. Typically, an office has an ambient light level of around 320 lux and in a darker room, around 50 lux.[7,8] As an estimate, using only half this light level (25 lux) for switching ON the largest ring-shaped pixel, we calculate that sufficient light is available to operate the LCD using commercially available resistors. Details of the calculation may be found in Appendix 1.

A mass produced integrated chip

A population-based study demonstrated that approximately 10 000 people lose an eye in the United States each year.[9] A mass produced cheap solution, which would fit the requirements for many patients, would be economically advantageous. The minimum and maximum size of the human pupil is about the same for all human beings assuming they do not have an iris disease. The pupil diameter variation under light is also close to being the same for everyone. Figure 4 (Left) shows the design of a standard device that could be integrated into most ocular prosthesis.

The circuit components (diodes and resistors) must be chosen to well represent the patient's average pupil diameter variation. After mass production, each device can be easily modified to accommodate the patient's pupil using a well-known technology: resistors laser trimming.[10] By trimming the resistors, their resistance can be tuned and therefore the light intensity needed to vary the pupil diameter changed, as explained before. Choosing the number of electrode rings can also fine tune the graded opening of the pupil as a function of the ambient light conditions to provide a more natural appearance. We believe that three or four rings should suffice for a good appearance. Note that the integrated integrated circuit chip can be fabricated directly into the back surface of the SC wafer.

Results and discussion

The objective of the following experiments is to demonstrate the principle of the device. Future work for a complete prosthesis with a dynamic pupil is also discussed.

Ring-shaped pixels simulating dilating pupil

To demonstrate the principle, a simple LCD sample with ring-shaped ITO electrodes was fabricated. Figure 5 shows the simulated operation of the pupil. Figure 5a shows the iris when there is low light and Figure 5c, under high ambient light conditions. Note that behind the LC cell will be an iris image and the SC would become the minimum opening of the black-colored pupil. This handmade LC cell, which is a working adjustable pupil, has survived heating to 120 °C for 1.5 h. The fact that the LC cell was not well sealed generates a few air bubbles making small black spots. Note also that the delineation of the electrodes will not be seen with microfabrication etching using a suitable electrode mask, and difficult to see with the color rendition of the iris. Note also that this handmade LC cell needed a voltage of 10 V to operate because of the large distance (12 μm) between the two glass plates.

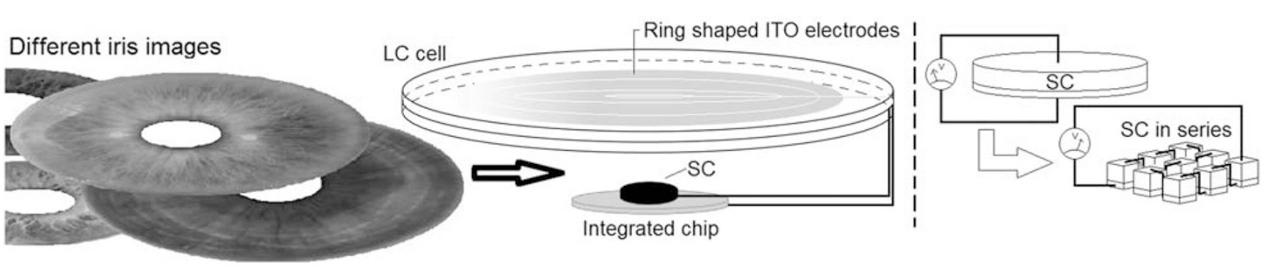

Figure 4 Left: design of a standard dynamic iris device for a massive production. Right: standard and high voltage SC array design.

The first LC cell surviving the ocular prosthesis manufacturing process

To test the survivability of LC cells for processing at high temperatures and pressures, a number of LC cells were fabricated in our laboratory. Different dimensions were used to test the robustness and the functioning of the cell after processing. The liquid crystals chosen (MLC-6647 from MERCK) for our application are rod-like shape in the nematic phase, which is the most widely used in the LCD applications,[4] but specially selected for their wide operating temperature range. Note that as the cell is only a few microns thick the volume of the LC required to operate the device is tiny ($<0.5\,\mu$l) and is therefore very low cost, as is true for most LCDs.[4,11,12] Because of the high pressure in the encapsulation process, thin glass cover plates were found to curve and generate fringes in the one-inch square or larger LC cells. We found that LC cells of dimensions 25×25 mm square for example, required a minimum glass plate thickness of approximately 1 mm. Having proved this requirement, cells used for the evaluation were samples from LC-TEC (FOS-25 $\times$ 30-TN-W), which were 25×30 mm with a total thickness for the assembled cell of 2.4 mm, including the glass plates.

A standard approach was used to manufacture a test device. The first step for the ocular prosthesis manufacturing process is to encase it in wax. Note that ocularists use their own specific recipes for the fabrication of the prosthesis, but there are many similarities.[13,14] A stone/plaster mould of the LC cell with wax is made to accommodate extra space for the acrylic to surround the device, as shown in Figure 5d.

The composition of the ocular prosthesis is a mix of poly (methyl methacrylate)/methyl methacrylate monomer. The liquid methyl methacrylate monomer monomer is added and mixed in a glass jar with poly (methyl methacrylate) clear polymer with a proportion of polymer: 3.5 to monomer: 1 by weight. The acrylic preparation is mixed occasionally for uniformity and left to rest until it achieves dough consistency, within 20–30 min, depending of the ambient temperature (faster when the temperature is higher). Once the mould has hardened, it is opened and the LCD with wax is removed and cleaned of any wax residues. Once the acrylic dough mix is ready, the LCD is surrounded with the mix, so that is totally encapsulated, see Figure 5e. The encapsulated LCD is placed in the mould, which is assembled together and placed under pressure using a clamp. The whole assembly is placed in a high pressure heat-curing unit set initially at three bar, for 30 min at 105 °C and then 30 min at 120 °C. After this curing process, the pressure is released and the mould is immersed in tap water to cool. The mould is opened and the device is taken out of the mould and then hand polished with various fine abrasives to make it clear and examined for transparency and clarity, as shown in Figure 5g. Figures 5g and h demonstrate, for the first time to our knowledge, the first LCD surviving the ocular prosthesis manufacturing steps.

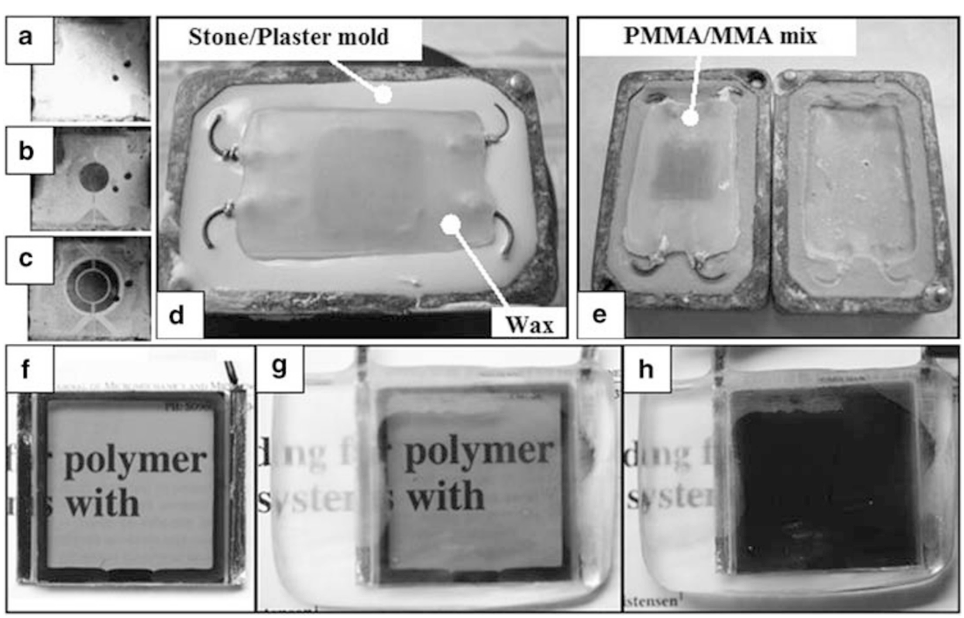

Figure 5 (a, b, c) Handmade ring-shaped electrodes LC cell. (d) Mould fabrication. (e) poly (methyl methacrylate)/methyl methacrylate monomer encapsulation. (f) LCD alone. (g) LCD surviving the ocular prosthesis manufacturing steps, after a rough hand polish, with the LCD in the ON state. (h) LCD in OFF state, showing the uniformity and contrast.

Considerations on the final device

Considering that the ocular prostheses are approximately 10 mm thick depending on the implant, the 2.4-mm thick LCD can be easily integrated. We used a 25 × 30 mm LC cell because it was commercially available (courtesy of LC-TEC) but smaller LC cells more appropriate for the iris size of about 13 mm diameter are being addressed. Currently, we do not envision a reduction in the thickness of the glass cell, however, for smaller diameters, a thinner glass could be used. Also note that all electronic components require almost no space, as these can simply be made into a single integrated circuit chip measuring much less than a mm square. However, with thinner glass cells, transparent spacers must be inserted between the two glass plates in the center of the cell to ensure that the plates do not collapse at high pressures, although smaller diameters will help eliminate this requirement. In our case, the transparent supports in the middle of the LCD will not affect the system because the light does not need to be switched in the smallest pupil size area. Moreover, lack of polarizers in that region would give more light to the SC, which would simulate the pupil color quite well.

Four iris images of the encapsulated LCD (see Figure 5g), which survived the ocular prosthesis manufacturing steps, are shown in Figures 6a, b, c, and d. These images would be the final result after adding the ring-shaped ITO etching patterns (Figure 2), inside the ON/OFF cell shown in Figures 5g and h. The pupil size has to follow the size of the healthy eye. The best relation between the diameter of the human pupil and the intensity of the incident light is:[15]

$$\log D = 0.8558 - 0.000401(\log B + 8.1)^3$$

where D is the diameter of the pupil in millimeters and B is the luminance of the visual field in millilamberts. However, age, eye color, sex, drugs administered, ametropia, pathological conditions and the stimulus field of the patient affect the pupil size.[15] Our proposal is to photograph the patient's eye under different light intensity conditions and to fabricate concentric ring electrodes on a backdrop of this painted iris.

The polarizers used in the LCD cut out a significant percentage of incident light. The important factor to note is that despite the reduction in the transmitted light, it appears that there is little difference in the rendition and in the visibility of the iris in Figures 6a, b, c, and d. However, the image through the LCD shown in Figures 6a, b, c, and d is initially a lighter one. It is clear that it would be difficult to make a dynamic LCD iris similar to a very light color iris, as shown in Figures 6e, f, g, and h. Figure 6e is a real iris viewed under high ambient light. The objective would be to make a similar image with polarizer. The Figure 6f is the same iris image under a 50% transmission polarizer. The difference between those two pictures is easily notable even if the black of the pupil LC pixel is perfect. Figures 6g and h are under a 70% transmission polarizer but Figure 6h uses a 20% lighter image. The result gets closer to the first real iris (Figure 6e) but the demarcation between the small pupil (LC cell) and the ring LC pixel may be just noticeable. This problem may be solved by changing or removing the polarizer over the smallest pupil diameter as the light does not need to be switched in that region.

On the other hand, a dark eye, which is the most common in the world,[16] would be relatively easy using a lighter image under the LCD. Polarizers with a transmission of over 35%, which are easily available, would be necessary to obtain a good contrast. Using a less efficient polarizer, which has poor extinction, would give better transmission in the ON state. In the OFF state, the poorer extinction would be complimented by the dark background of the silicon substrate. The silicon SC

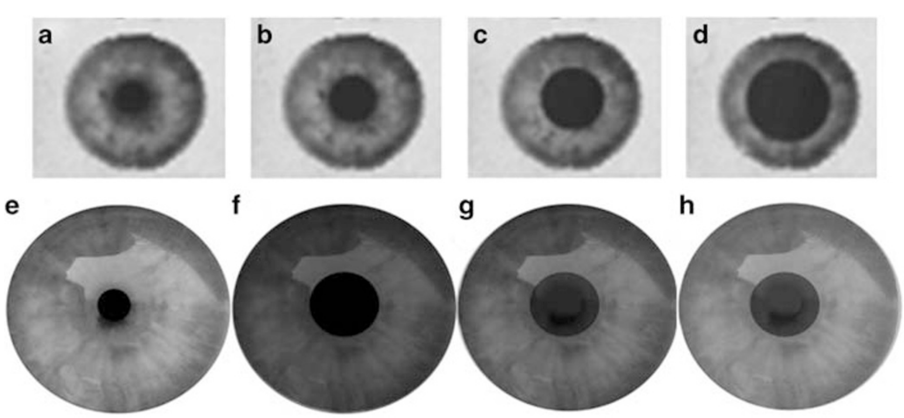

Figure 6 (a, b, c, d) Iris images through the LCD surviving the ocular prosthesis manufacturing process. (e) Photograph of a light iris under high ambient illumination. (f) Same image with a 50% transmission polarizer. (g) Under a 70% transmission polarizer. (h) A 20% lighter image under a 70% transmission polarizer. Figures f, g, h are simulations with OFF state ring-shaped LC pixels.

Figure 7 Demonstration of the passive circuit, showing increasing ambient light from left to right. The different activated segments represent the decreasing pupil size using this entirely self-powered scheme.

proposed here would help to emulate a perfectly black pupil despite the reduced transmission through the polarizers. The polarizers must be selected appropriately depending on the color of the iris. With a dark iris, for example, a poor polarizer may be used, resulting in a better contrast and a near black pupil.

The passive circuit demonstration

Finally, to demonstrate the working principle of the passive circuit, Figure 7 shows the device in operation using a clock LCD. In the dark, none of the pixels operate (left most picture). In the Figure 7, from left to right, the light level increases monotonically. Nine tiny interconnected SCs are used in series. More than nine SCs in series (delivering a potential higher than we needed for our demonstration) have already been reported,[6] so that it is a scalable solution. The size of the passive circuit (bottom of each picture) is less than 8 mm diameter and will be hidden by the image of the iris in the final ocular prosthesis (or integrated into the silicon cell), once fully integrated. Note that in this LCD there are crossed polarizers.

Summary

What was known before

- No one has succeded to demonstrate an autonomous dynamic pupil in an ocular prosthesis.

What this study adds

- A practical solution for an autonomous self-powered dynamic pupil in an ocular prosthesis is possible. The first LCD surviving the rugged conditions of the ocular prosthesis manufacturing steps and an entirely passive circuit controlling the pupil have been demonstrated for the first time.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

This project is supported by a grant from the Canadian Institute for Photonics Innovation (CIPI) Technology Exploitation Grant, and RK acknowledges the support from the Govt. of Canada's Canada Research Chairs Program. We would also like to thank Jean-Sebastien Décarie and Jules Gauthier's team for their expert technical assistance.

References

1 Leuschner FW. Light-controlled pupil size for ocular prosthesis. *Proceedings of ophthalmic technologies II* 1992; **1644**: 320–325.
2 Seekolaq DL, Leuschner FW. Use of liquid crystal display technology in ocular prosthesis. *Liquid crystal materials, devices and displays* 1995; **2408**: 100–106.
3 Lapointe J, Kashyap R, Boulos PR. Prosthetic eye with a dynamic liquid crystal pupil. P1217USPR (US provisional Patent applied for). 2010.
4 Lueder E. *Liquid Crystal Display: Addressing Schemes and Electro-Optical Effects*. John Wiley: Chichester, 2001.
5 Green MA, Wenham SR, Zhao J. Progress in high efficiency silicon cell and module research. *Conference Record of the IEEE Photovoltaic Specialists Conference* 1993; 8–13.
6 Lee JB, Chen Z, Allen MGA. Miniaturized high-voltage solar cell array as an electrostatic MEMS power supply. *J Microelectromechanical Syst* 1995; **4**: 102–108.
7 Pears A. Strategic study of household energy and greenhouse issues Brighton (Au): Sustainable Solutions Pty Ltd; 1998 June. *A report for Environment Australia*.
8 Pérez J-P. *Optique: Fondements et Applications*. 7th edn. Dunod: Paris, 2004.
9 Peter AD, Rubin MD. Enucleation, evisceration, and exenteration. *Curr opin ophthalmol* 1993; **4**: 39–48.
10 Oakes M. An introduction to thick film resistor trimming by laser. *Optical Engineering* 1978; **17**: 217–224.
11 Collings DPJ, Hird M. *Introduction to Liquid Crystals*. Chemistry and Physics CRC Press: Excelsior, 1997.
12 Chandrasekhar S. *Liquid Crystals*. 2nd edn. Cambridge University Press: Cambridge, 1992.
13 Raizada K, Rani D. Ocular prosthesis. *Contact Lens & Anterior Eye* 2007; **30**: 152–162.
14 Bartlett SO, Moore DJ. Ocular prosthesis: a physiologic system. *The journal of prosthetic dentistry* 1973; **29**: 450–459.
15 Groot SGD, Gebhard JW. Pupil size as determined by adapting luminance. *J Opt Soc* 1952; **42**: 492–495.
16 Eiberg H, Mohr J. Assignment of genes coding for brown eye colour (BEY2) and brown hair colour (HCL3) on chromosome 15q. *Eur J Hum Genet* 1996; **4**: 237–241.
17 Luque A, Hegedus S. *Handbook of Photovoltaic Science and Engineering*. Wiley: Chichester, 2003.

Appendix 1

In this section, we provide details for the reader interested in the calculation for the operation of the SC and the LCD.

We take the example of a minimum diameter of the pupil of just over 3 mm. Nine SCs in series are fabricated in this area. Each one of the nine SCs will receive about $P = 37$ nW on its 1 mm square surface (about 0.5 mW under an office illumination).[8] For a typical multiple-junction SC, the quantum efficiency η is more than 60% and the conversion efficiency ρ is more than 15%.[17] The current generated by the SC is then $I = \eta\rho P = 4$ nA. 3.5 V is required to operate the first pixel, which may be achieved with a resistor $R = V/I = 875$ MΩ. Therefore, the device should operate using resistors of between 500 and 900 MΩ. These resistor values are easily available (See for example: http://www.cermetresistorsindia.com/high-voltage-resistors.html).