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Eye model with controllable lens scattering

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ABSTRACT

A model of human eye for experiments in vision research has been developed using PLZT ceramics. This "artificial eye" allows to simulate light scattering caused by cataract in the eye lens. Light scattering of a composite eye lens of the model depends on the electric field applied to a transparent electrooptic PLZT ceramics plate that is attached directly to the lens. The image degradation in such a model eye at various degrees of scattering is studied observing and recording the contrast of images on the ''retinal plane'' created by standard test objects with different spatial frequency or by a He-Ne laser source passing a diffractive transparent placed before the eye.

Keywords: model of eye, light scattering, cataract, electro-optic ceramics.

INTRODUCTION

The lens of the human eye can be described as a transparant with soft scatterers of single type.[1] It has been shown that the transparency of the lens is largely the result of the highly ordered arrangement of the macromolecular components of the lens cells and of the small differences in refractive index between the light scattering components[1,2] Most disturbances of transparency of the eye lens tissues can be approximated by a loss of the regular arrangement of spherical scatterers, along with the increase in their size and number.[1]

Disturbances of lens transparency resulting in visual impairment are defined as cataract. Cataract is the largest single cause of blindness worldwide.[2] According to the extent of opacity cataract is classified as immature, mature or hypermature. Discerning development of cataract to the hypermature stage is a task of particular clinical importance as proteins may escape from the lens capsule that leads to inflammations.[3]

A peculiarity of the lens of the human eye is that it grows steadily throughout the lifetime. Its thickness in human beings increases by 0.02 mm per year due to perpetual cell division in the outer equatorial zone of the lens.[2] New long fibers are reaching toward the poles of the lens, former fibers are displaced toward the center. Therefore this cells in the nucleus of the lens suffer structural changes.[4] Alternatively a necrotic process can develop in the outer – cortical – cells, a cloudy swelling of fibers occurs. Later the region of the lens is filled with globules, coagulate of insoluble proteins, fatty droplets and detritus, which induce considerable light scattering. Their refractive indices differ from the one of the healthy lens, which is comparably high - 1.420.[2]

A variable degree of light scattering can be induced in some materials, for instance, in electro-optic PLZT ceramics (abbr. PLZTX/65/35 is used for a solid solution $Pb_{1-X/100}La_{X/100}Zr_{0.65}Ti_{0.35}O_3$)[5] or polymer dispersive liquid crystals.[6] The scattering parameters of these materials depend on controllable external factors, particularly on the applied electric field. It has been shown that at the values of the applied electric field $E \approx 8$ kV/cm the effective scattering coefficient of some PLZT ceramics compositions is 15-30 cm^{-1} at wavelenghts 660-450 nm, [7] that is comparable with that of a cataract eye.

Assessment of the retina and the optic nerve of the cataractous eye may be necessary to predict visual functions after the extraction of an opaque lens and replacing it with an intraocular lens. In the case of cataract the reaction to the light stimuli can be evaluated by interferometric diagnostics. Using such technique the patient should not need to have an exact accommodation to the stimulus, and a presence of some clear spots within the pupil area ensures creating of the interference pattern on the retinal plane. Varying of the interference pattern on the retina by altering parameters of the diffractive transparent enables to predict the maximum visual acuity in the eye after the extraction of cataract if that appropriate optical correction is applied.[8,9,10]

The main tasks of the work presented were: a) to develop a model, where light scattering properties of ''the lens'' could be continuously controlled, and - b) to investigate how the contrast of images on the ''retinal plane'' formed by standard test objects or by diffraction patterns depends on the induced light scattering in the lens.

EXPERIMENTAL AND RESULTS

A plate of PLZT ceramics was used as the active scattering media in our eye model. PLZT ceramics is La modified lead zirconate titanate, which have a pronounced electro-optic effect.[5] This ceramics has polycrystalline structure and are transparent in the visible spectral range. Therefore under standard conditions the crystals of size of some microns are randomly oriented, and the matter is optically isotropic with the refractive index ≈2.5.[5] The external electric field can cause formation of small size polar microdomains. Alteration of the applied electric field changes the size and refractive index of these microdomains that causes essential induced light scattering that depends on wavelength (Fig.1).[7] It has been shown previously that a PLZT ceramics obstacle placed before the eye can essentially decrease the visual acuity (Fig.2).[11]

The scheme of the experimental set is shown in Figure 3. In order to obtain the optical power of the model eye close to the power of the human eye,[8] a small plane-convex glass lens with optical power F=56D is glued on a plate of PLZT 9/65/35 ceramics (thickness b = 1.5 mm) which is the volume of controllable light scattering of the model.

After passing the refractive and scattering media beams are focused on the ''retinal plane'' that is located approximately 1.8 cm from the nodal point of the model eye. The image formed by the model eye is observed by a binocular microscope with magnifications ranging from 4.8 to 98. Thus the image formed by the microscope can be observed by

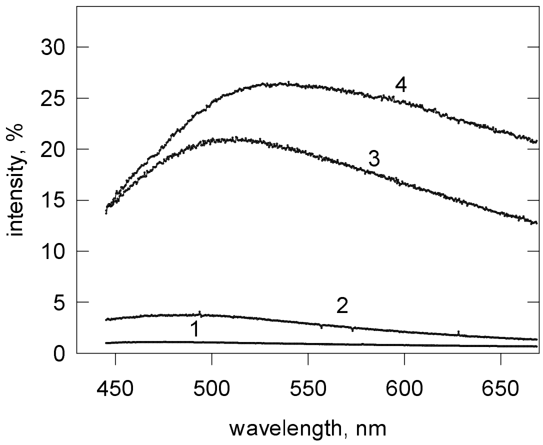


Fig.1. Spectral characteristics of the PLZT 9/65/35 ceramics plate for total forward scattered light normalized to the incident illumination.
1 - plate without electrodes, applied electric field **E** = 0 kV/cm;
2 - plate with semitransparent Au electrodes, **E** = 0 kV/cm;
3 - plate with electrodes, **E** = 10.7 kV/cm
(**4** - transmission of the 1.5 mm thick PLZT plate without electrodes).

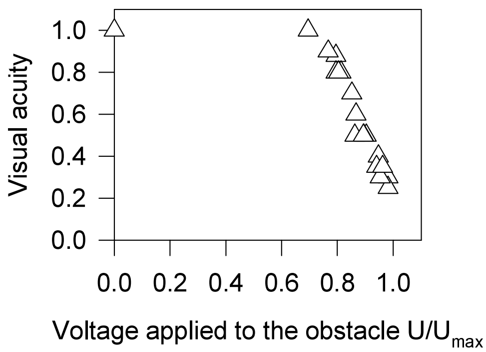


Fig.2. Dependence of monocular visual acuity VS *versus* voltage applied to the light scattering obstacle[11]

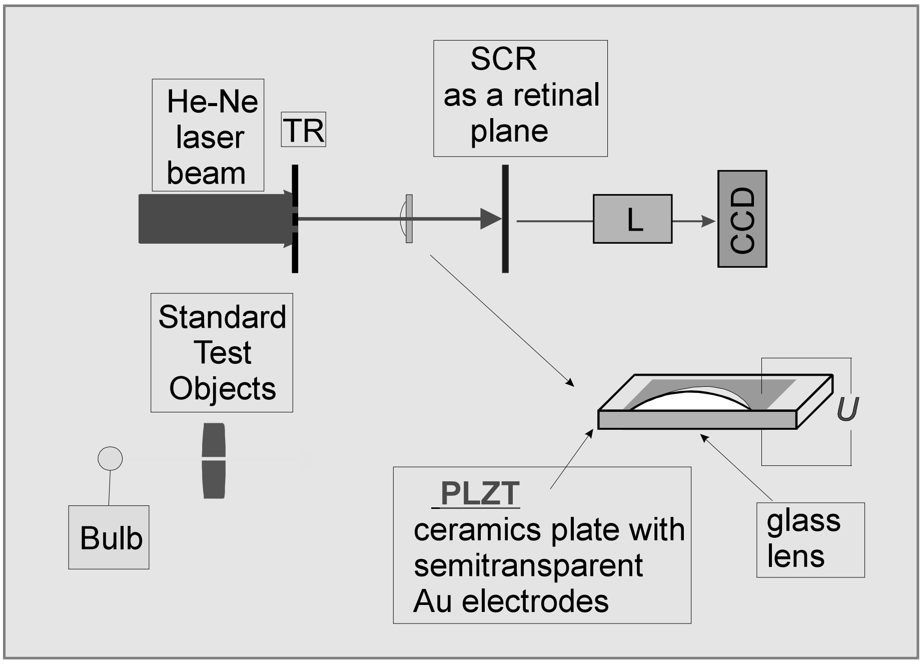


Fig.3. Experimental set-up for investigation of the image contrast formed by the eye model with electric field induced light scattering using laser light interference caused by diffractive transparent or standard test objects.
TR - transparent,
L - system of lenses,
CCD - digital camera,
SCR - screen,
U - voltage applied to electrodes.

an experimenter's eye and can be with visualized with a digital camera. A human eye with normal visual acuity can resolve two images separated by app. 5 microns on the retina (that corresponds to angular resolution of 1 minute of arc). The CCD used in experiments (a conventional *Olympus C2500* photo camera) together with the binocular microscope was not the best experimental solution, the line resolution in digital images was restricted due to transversal chromatic aberrations. To study the decrease of the visual acuity caused by the increased scattering in the lens we have projected images on the ''retinal plane'' of the model eye by two methods. Firstly, a set of standard test gratings with various spatial frequency was used. Secondly, we used a collimated monochromatic source of light (a He-Ne laser beam, wavelength λ=0.633 μm), which allows to observe diffraction patterns and to reduce the impact of chromatic aberrations on the spatial resolution of the model.

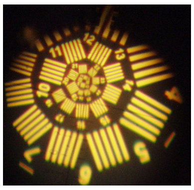
When investigating the retinal visual acuity lower order diffraction maxima are of the primary interest. The minima are seen as dark gaps between bright maxima, which is similar to the Gabor contrast pattern of test objects used in ophthalmology. The condition to find maxima of diffraction behind a diffraction grating is

$$\mathbf{d*\sin\phi=m\lambda,}$$

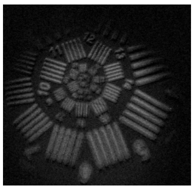
where **d** is the period of the transparent grating, ϕ is angle formed by the diffraction maxima behind the grating (ϕ equals to 1 arc minute to test the conventional visual acuity), **m** is the order of a maximum and λ is the wavelength of incident light.

In clinical use evaluation of the retinal visual acuity with the interference patterns has an advantage as compared with the use of illuminated test objects. Regions of constructive and destructive interference are formed on the retina independently from the state of patient's accommodation and the refractive state of the eye. However, if the opacity occupies the whole optical region behind the aperture, the contrast of the interference formed image can be impaired, eventually lowering the results of retinal visual acuity testing.

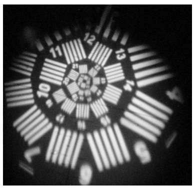
The standard test object contained a set of parallel transparent lines with different spatial frequency on a non-transparent background. It was illuminated with a conventional incandescent light bulb. Observing the image of the object on the "retinal plane" in microscope with the eye, the maximum angular resolution of the system "lens + PLZT plate with



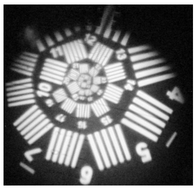
composite image
all color channels
present



blue
channel



green
channel



red
channel

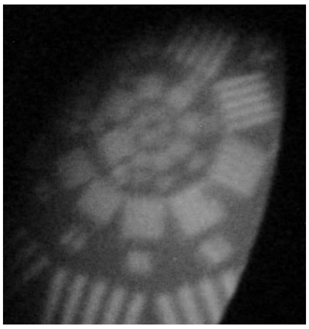
Fig.4. Images of the standard test object formed by the eye model. No voltage applied to PLZT plate.
Pattern #5 corresponds to the angular resolution 4.3 arc min (1.44 lines per mm at the distance between eye and test object D = 280 mm), pattern #10 - 2.5 arc min, pattern #18 - 1.2 arc min.

semitransparent electrodes” was greater as compared to the angular resolution of the human vision (1 arc minute). Using the digital imaging the resolution of these images was lower. However, as we were looking for the degree of the image degradation up to levels corresponding to *visus* VS = 0.5 and below, we found the digital imaging satisfactory.

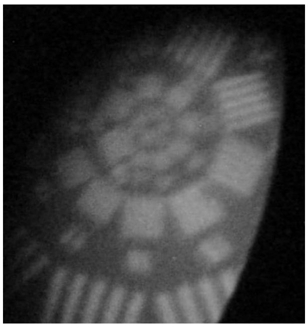
Fig.4 shows the pictures of the standard object for such system with no electric field applied to the PLZT plate electrodes, as well for the composite (all color channels) as for each channel - blue, green and red separately.

Applying the voltage U to electrodes leads to the following sequences. Observable changes of the image degradation begin at values of the electric field E = U/b =5-8 kV/cm. At these E values, firstly, the fraction of the non-scattered image forming light decreases that leads to the decrease of the image intensity. The image at short wavelength range, in the blue image channel by separating the image color channels, is less intense already due to greater absorption of PLZT ceramics and electrodes. Light scattering effect also is more evident at short wavelengths thus the image degradation seen for blue channel image occurs at lower values of the applied voltage U. Secondly, the contrast of the pattern $C=(I_{max}-I_{min})/(I_{max}+I_{min})$ also decreases increasing the applied voltage, and more evident for blue channel as compared to green and red image channels. Fig. 5 shows the green (left column) and red (right column) pictures of the test object if the intensity of the applied electric field equals to E= 8.4 kV/cm (upper row) and 9.0 kV/cm (lower row).

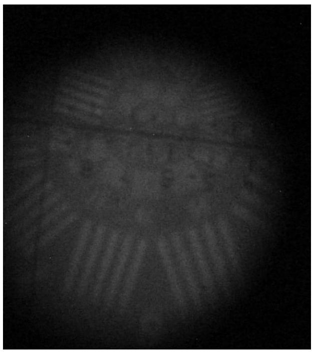
To evaluate the image contrast changes by applying the electrical field a single bit line was scanned along the direction perpendicular to the grating lines for the pattern #13 (the angular resolution of the pattern - 2 arc min, corresponding to the visual acuity VS = 0.5, measuring it by conventional techniques). Results are shown in Fig.6. It can be seen from Fig.5 and Fig.6, that at values of the electric field E = 9 kV/cm the light in blue spectrum range is practically fully scattered and is unable to form an image for sufficient visual acuity.



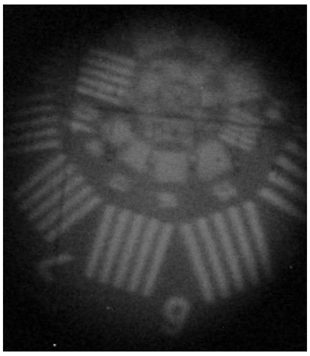
green channel
E = 8.4 kV/cm



red channel
E = 8.4 kV/cm



green channel
E = 9.0 kV/cm



red channel
E = 9.0 kV/cm

Fig. 5. Images of the standard test objects formed by the model eye when the electric field E is applied to the PLZT plate.

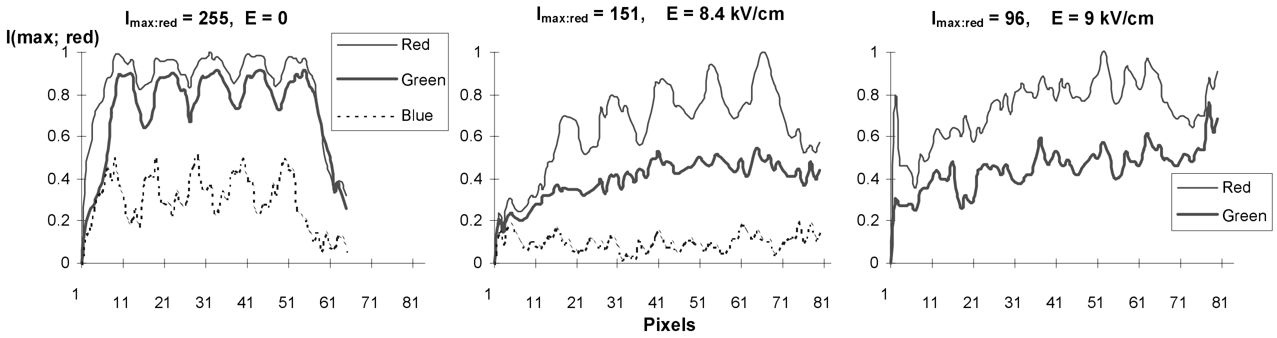


Fig. 6. Image intensity scans along the direction perpendicular to the pattern #13 lines for separated blue (dashed line), green (bold) and red (single) image channels at various values of the applied electric field E.
Pattern #13 period - 3.5 lines/mm, distance between eye and object 280 mm, angular resolution 2 arc min. Intensities for each diagram are normalized to the maximum value of the red channel intensity $I_{max:red}$.

Image formation of the model eye in conditions similar to those used for interferometric evaluation of the retinal visual acuity was simulated using a double slit diffraction grating with a distance between slit centers d = 1 mm. For the used He-Ne laser (λ=0.633 µm) such a double split forms more or less sinusoidal spatial interference distributions with the angular distance between maxima 2.2 arc min (corresponding to the conventional visual acuity VS = 0.46). Fig.7 shows the interference patterns observed on the retinal plane for the nonscattered eye (E=0) and those for the applied electric field values E = 8.4 and 9.0 kV/cm. Fig.8 shows the one bit scanned intensity distribution along the line through the spot centers. The intensity values for the lines 1, 2 and 3 are not proportional each to another, we did not ensure the exactly equal exposition and camera in-build digital preprocessing. The diagrams obviously show the degradation of the images below the Raleigh criterion due to the induced controllable scattering also for the longer wavelength range for the angular resolution corresponding to VS = 0.46.

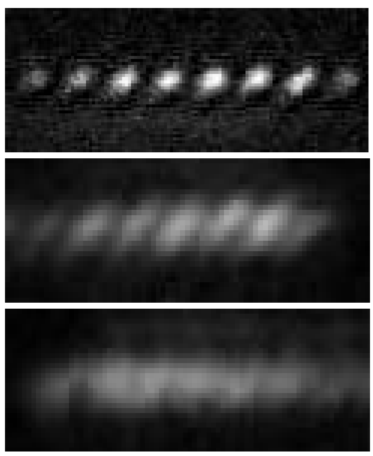


Fig 7. Diffraction patterns at the retinal plane formed by double slit (slit separation - 1mm, wavelength - 0.633µm, corresponding angular resolution 2.2 arc min) without electric field applied (upper figure), E= 8.4 kV/cm (middle); 9 kV/cm (lower).

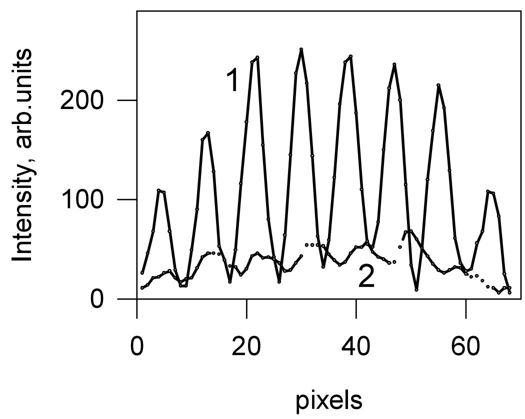


Fig. 8. Intensity scans of the diffraction patterns formed at the retinal plane without electric field induced scattering (1), E= 8.4kV/cm (2).

CONCLUSIONS

Scattering induced by the external electric field applied to the active structure of the eye modell - an electropoptic PLZT ceramics plate decreases the angular resolution of the eye below the visual acuity 0.5 at the electric field values E = 9 kv/cm. The developed eye model can be used for simulation of the image formation in eyes with essential scattering of the eye.

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