

# Thin spectacles for myopia, presbyopia and astigmatism insensitive vision

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**Abstract:** The aim of the presented research was to develop special spectacles capable of solving common ophthalmic problems as myopia, presbyopia and regular/irregular astigmatism. The method included adapting special all-optical extended depth of focus concept, taken from the field of digital imaging, to ophthalmology, and by that providing the required vision solutions. Special thin mask containing annular like replicated structure (thickness of the structure is less than one micron) was designed and proven to provide extended depth of focus. In this paper we present several experimental results as well as trials with volunteers. The testing included measuring the visual acuity under different illumination conditions (pupil size varied from 2 up to 4mm), as well as stereoscopy, color integrity, field of view and contrast. The results demonstrate improvements of up to 3 Diopters (for presbyopic that require the bifocal or the progressive lens solutions) for pupil sizes of 2-4mm. The approach has demonstrated improvement of more than 2 Diopters for regular as well as irregular astigmatism. The main advantage of the developed optical element is that it is very thin (less than few microns) and has low price, it has high energetic throughput and low chromatic aberrations and it operates over the full field of view while providing continuously focused image (in contrast to bifocal lenses having only 2 focused regions). The element also provides a solution for regular as well as irregular astigmatism that currently has no available treatment.

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## 1. Introduction

Focused and highly resolved imaging is a mandatory requirement in any imaging system. Therefore attempts of extending the depth of focus are intensively investigated in digital imaging as well as in ophthalmic applications. The main problem with the developed solutions for extended depth of focus (EDOF) is that they require digital post processing and therefore are applicable only to digital imaging (i.e. for digital cameras) but are not suitable for ophthalmic applications [1-3]. Other approaches of EDOF are all-optical but they are based upon either apodization of the lens aperture (and by that reducing the energetic throughput while reducing spatial resolution) or on diffractive optics (i.e. optical elements having spatial features as small as the optical wavelength and therefore encountering high diffraction effects. The diffraction effects are expressed by having multiple diffraction orders which are generated outside the region of interest) and therefore suffer from low energetic efficiency [4-7].

Recently a new and an all-optical approach for EDOF was developed and demonstrated experimentally [8,9]. At first this new approach was implemented for digital imaging [9].

In this paper we present the adaptation of those concepts to ophthalmic applications. The idea behind the operation principle is to develop a phase-only (a transparent) element with large spatial features that will yield a reduced sensitivity to quadratic phase factor (that is obtained when the image is defocused) under the mathematical operation of auto-correlation.

Note that the auto-correlation operation of the phase distribution in the aperture plane is obtained anyhow when the Optical Transfer Function (OTF) of the imaging system is computed. Working with OTF is correct when spatially non coherent illumination is used. Since all the relevant cases involve this type of illumination, the operation of the element suits the ophthalmic set of applications.

Because the element has large spatial features and it is a phase only element, it has high energetic efficiency (there are no diffraction orders except of the zero order) and it is not sensitive to chromatic aberrations. The element itself has a binary phase annular like shape which is periodically or randomly replicated over the area of the spectacles. This shape when encounters the quadratic phase of defocusing, which arrives to the aperture plane, reduces the effect of this quadratic phase under the mathematical operation of auto-correlation (the OTF is the auto-correlation of the field distribution in the pupil plane). The replication of the annular like phase shape is required in order to have uniform performance over wide field of view of the spectacles.

The binary phase includes etching depths of approximately 1 micron and therefore the EDOF element itself is very thin. In addition to that it has no optical power. The feature size of the annular like phase is large in comparison to the optical wavelength and therefore the diffraction effect is negligible (there is only the zero diffraction order). Basically the annular shape element is responsible for redistributing the energy around the zero diffraction order such that the focused region is axially extended. The trade off that this extension causes is the reduction in the contrast of the high spatial frequencies (although all frequencies are still resolved). This reduction of contrast is not large and can be overcome and compensated by the brain as we have observed in the tests that we have conducted with a group of volunteers.

Figure 1 schematically presents the effect of the EDOF element and the energetic redistribution that is generated in the focal plane of the imaging lens. Although this

explanation is very brief, the full operation principle is extensively explained in Ref. [9]. This manuscript focuses on presenting the research results obtained after adapting this EDOF technology to the ophthalmic market and especially for spectacles.

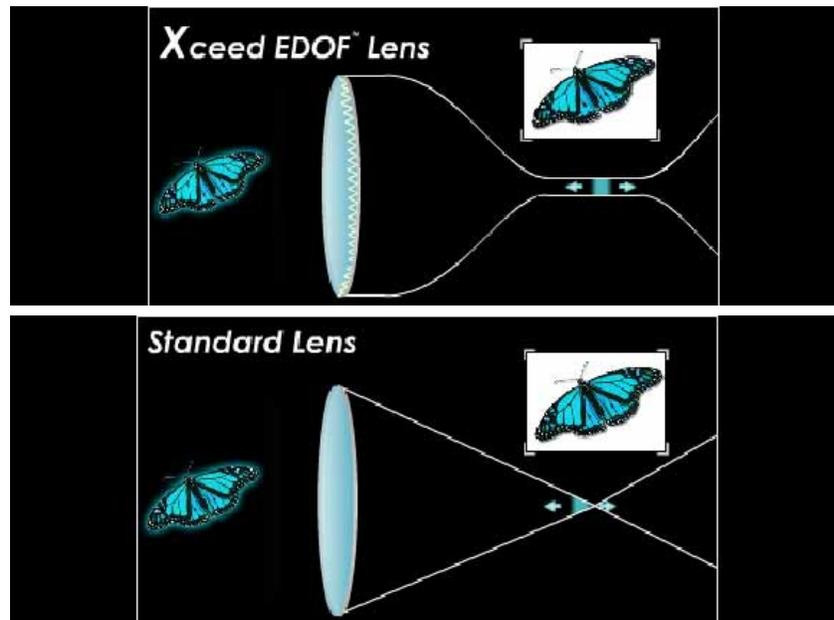


Fig. 1. Schematic sketch of the effect of the EDOF element.

After the age of 45 the majority of people begin to experience presbyopia, difficulties in focusing on near objects due to a reduction in accommodation, i.e. in the ability to alter the focal distance of the eye lens. This reduction in the accommodation is continuously progressing until the eye is permanently focused at a single distance whose position depends on the optical properties of the eye. This is currently remediable by reading glasses or spectacles with two or more foci to have acute vision for few distances (bifocal [10] or multifocal lenses [11,12]). In these lenses the two (or more) focal lengths are spatially separated and allow the required performance only over a small portion of the field of view. Therefore those solutions are suboptimal and do not restore the prepresbyopic visual performances.

Another very common problem is related to astigmatism. The meaning of the term is that the lens of the eye has developed different focal lengths in two different axes. Those axes may be orthogonal (i.e. perpendicular) to each other as in regular astigmatism [13] or not as in irregular one [14]. Currently there are no available solutions for irregular astigmatism and even the regular one is not fully treated.

In this manuscript we show how our EDOF solution (which can be fabricated on the outer, inner or both surfaces of a spectacle lens) allows energetically efficient and continuously extended vision over a wide range of distances and over large field of view.

We present experimental results as well as preliminary testing performed over small test group of volunteers indicating that the presented technology will indeed provide potential solution to the limitation of present day presbyopic correction as well as for regular and irregular astigmatism.

Section 2 presents brief description of the EDOF principle. Experimental results and their validation over a test group are seen in section 3. The testing is done over people with presbyopia as well as people with astigmatism. The paper is concluded in section 4.

## 2. Principles of extended depth of focus

Mathematically speaking, the OTF is defined as the auto-correlation of the spatial phase distribution over the aperture plane:

$$H(\mu_x, \mu_y; Z_i) = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P\left(x + \frac{\lambda Z_i \mu_x}{2}, y + \frac{\lambda Z_i \mu_y}{2}\right) P^*\left(x - \frac{\lambda Z_i \mu_x}{2}, y - \frac{\lambda Z_i \mu_y}{2}\right) dx dy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |P(x, y)|^2 dx dy} \quad (1)$$

While in focus,  $P(x, y)$  is the binary circle pupil function, which is “1” within the pupil, and “0” outside,  $\mu_x, \mu_y$  are the spatial frequencies,  $\lambda$  is the wavelength,  $Z_i$  is the distance between the imaging lens and the sensor and  $(x, y)$  are the spatial coordinates in the aperture plane.  $H$  is the OTF. The meaning of Eq. 1 is that the OTF equals to the auto-correlation of the transmission of the aperture plane.

When aberrations are introduced due to defocusing as well as due to addition of special phase only element to the aperture plane, the generalized pupil function can be described as:

$$P(x, y) = |P(x, y)| \exp[ikW(x, y)] \quad (2)$$

Where  $W(x, y)$  is the wave aberration and  $k = 2\pi/\lambda$ . If the aberrations are caused only by defocusing,  $W(x, y)$  has the form of:

$$W(x, y) = W_m \frac{(x^2 + y^2)}{b^2} \quad (3)$$

where  $b$  is the radius of the aperture  $P$ . The coefficient  $W_m$  determines the severity of defocusing.

The idea is to design a phase only element having large spatial features such that the auto-correlation operation of Eq. 1 will generate OTF that is invariant to quadratic phase distortion created when defocusing aberrations are introduced [9]. After posing this condition mathematically and deriving the expression, an optimal solution for the phase only element is obtained.

Although the operation principle for digital imaging was demonstrated in Ref [9], in the ophthalmic application of spectacles several research challenges were introduced. The first challenge is related to the fact that the spectacles are about 1.5-2cm (or even more than that) away from the aperture plane of the lens of the eye. For instance in digital imaging this problem does not exist since one may access the aperture plane and place the optical element there. The second challenge is related to the fact that the eye of the observer constantly varies its line of sight. The spectacles need to generate the effect of the phase element for wide field of view and not only for a certain line of sight. This is required in order to allow comfortable reading abilities in near range. In contact lenses or in Intra Ocular Lenses (IOLs) this problem does not exist since there the contact lens or the IOL with the EDOF element on top, move more or less together with the eye ball and its varying line of sight.

The solution to the first challenge was obtained by slightly changing the diameter of the annular like binary phase structure as well as by increasing the etching depth of the phase element (after this increase the etching depth was still less than 1 micron and therefore the element is still very thin). The solution to the second challenge was obtained by spatially replicating the basic structure of Ref. [9]. In addition in order to create improved performance the structure was generated on both sides of the glass of the spectacles and it was replicated either periodically or formed into a random structure. That way the EDOF performance was reinforced and obtained for larger range of diameters of the pupil of the eye.

### 3. Experimental investigation

#### 3.1 Presbyopia

Using the concepts briefly described in section 2 and analytically analyzed in Ref. [9] we have managed to obtain an outcome providing EDOF equivalent to 3.00D (D stand for Diopter and it equals to one over the focal length in units of meters), for eye's pupil diameters of 2-4mm (therefore it is applicable for wide range of illumination conditions) and with high tolerance to the precise position of the element in relation to the eye's visual axis. The solutions we present are applicable for presbyopia since obviously the 3.00D improvement is obtained for near vision while not affecting the high quality imaging of far vision. Note also that the element itself has no optical power and therefore when it is positioned in front of the eye it will provide the improvement within the range of 0.00D-3.00D and therefore no residual accommodation is required. If it is added to a lens of say 2.00D the operation range will be 2.00D-5.00D, instead.

Figure 2 depicts an image presenting the visual acuity (VA) resolution target showing on the right part the image obtained by a distortion of -1.75D lens (as it is seen through presbyopic eye which needs +1.75D correction) while the left part is the image that is obtained with our EDOF element. One may see that indeed improvement of 1.75D is visible (each line in the resolution target is equivalent to 0.25D and the last readable line is emphasized with red rectangle). The experimental results presented in Fig. 2 were obtained by building imaging system with optical parameters equal to those of the human eye [15]. The pupil diameter that was used in this experiment was 2.5mm while the phase element was positioned 17mm away from the cornea of the eye. Note that the elements that were tested had annular like structure with external diameter of 2.6mm for the ring (basically similar to the element that was described in Ref. [9]) replicated with basic period of about 3.5mm and etching depth of 350nm (equivalent to generated phase of about  $\pi/2$ ). The elements were fabricated on both sides of a flat glass having width of 2mm.

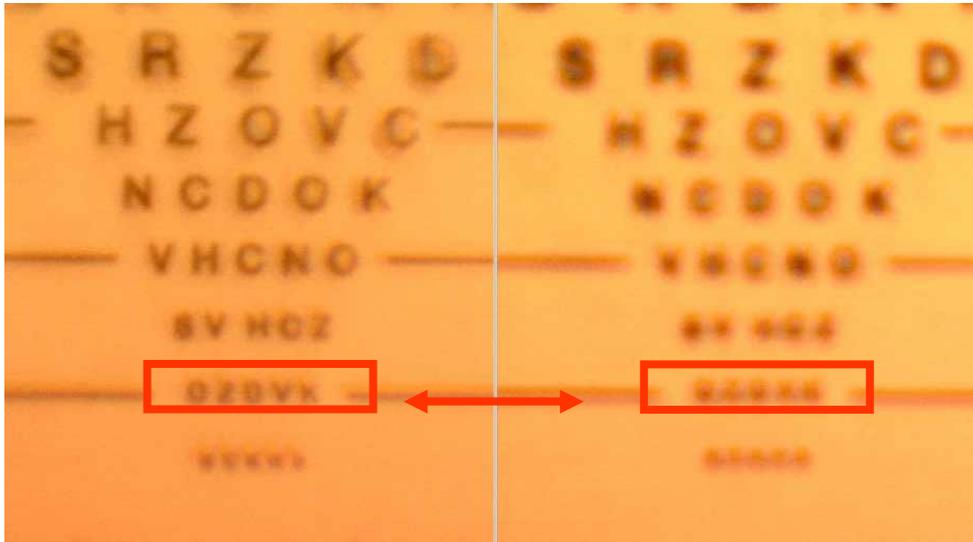


Fig. 2. Experimental demonstration for 1.75D. Left part with EDOF element. Right part without it.

The age and the ophthalmic specification of the people participating in the test group appear in table 1. All were free of pathology.

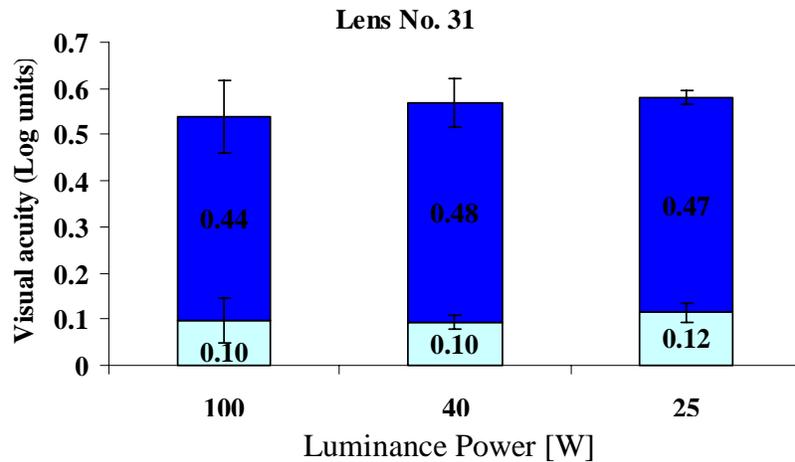
The first set of elements which we numbered as 31, 32, 33 and 35 (The numbers are for internal use and the variation between the various elements included a slight change in the diameter of the basic pattern and in its etching depth. The variations between the elements were of about 10% in the diameter and the etching depth.) was tested with 7 subjects at age range of 50 to 65 with an average age of  $55 \pm 5.2$ .

Table 1. Test group for the first experiment.

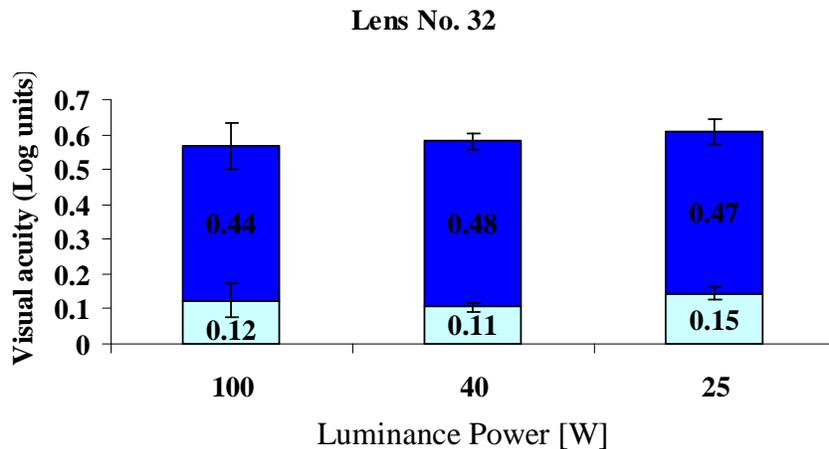
Subject No.	Age	Addition
1	50	2
2	50	2.5
3	65	3
4	53	2.5
5	56	2.5
6	52	2.25
7	53	2.25

The next step of development included the testing of the element on a test group. Figure 3 presents the obtained testing results. All of our subjects had corrected VA of 6/6 or better to far distance, before being tested with the EDOF elements. None of them had deficit in color vision or contrast sensitivity or any other type of pathology. All of the subjects were presbyopic and needed optical correction for near distance. VA tests were made with logarithmic charts, Precision Vision chart for testing at 40cm and Early Treatment Diabetic Retinopathy Study (ETDRS) for testing at far distance.

The subjects were tested at three different luminance conditions which affected the pupil size of their eyes; high luminance led the pupil size to be 1.5 to 2.5 mm, the middle luminance power set a diameter of 2.5 to 3.5 mm and the low luminance a diameter of 3.5 to 4mm. VA testes were taken with the EDOF element placed on top of the far distance optical correction. We found no significant differences in VA improvement using the EDOF element within the three luminance conditions. Element number 31 improved the near distance VA for the high, middle and low luminance to  $0.096 \pm 0.048$ ,  $0.95 \pm 0.014$  and  $0.115 \pm 0.048$  (in Log units), respectively.



(a).



(b).

Fig. 3. Visual acuity for near vision obtained over a test group with elements number: (a). 31 and (b). 32. The horizontal units are the illumination power of the illuminating lamp in Watts, the vertical axis is for VA in Log units. The dark blue bars present reading VA without near distance optical correction and the light blue bars present VA with the EDOF element.

The obtained results are presented graphically in Figs. 3(a) and 3(b). The horizontal units are the illumination power of the lamp in Watts, the vertical axis is for VA in Log units. The dark blue bars present reading VA without near distance optical correction and the light blue bars present VA with the EDOF element. Therefore the true improvement is the subtraction between the numbers of the dark and the light blue bars, e.g.  $0.44 - 0.1 = 0.34$  for element number 31 with illumination power of 100W.

In both parts of the figure the standard deviation is designated as black lines plotted on top of the presented measurement.

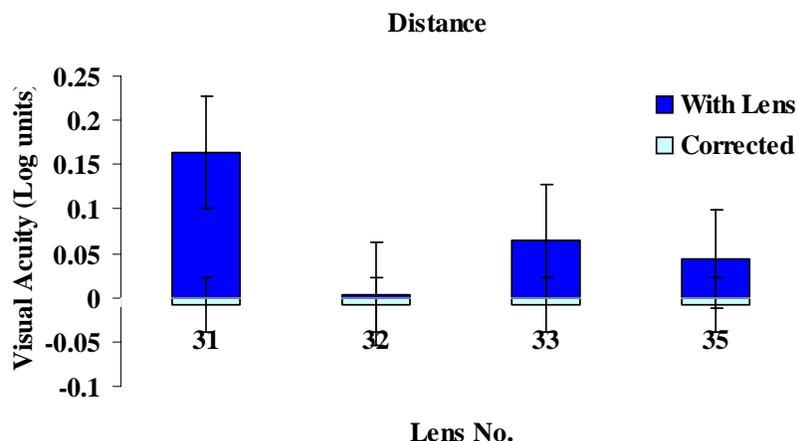


Fig. 4. Visual acuity for far field vision obtained over the same test group and with various types of elements.

In Fig. 4 we have presented the demonstration of the EDOF element for far field imaging. It can be seen that the same test group that had improvement of VA in near field has no degradation in the far field imaging quality (this is especially seen in element number 32). The results show small amount of deficit, less than 0.1 Log units in VA for most of the subjects. The distance vision tests of Fig. 4 are summarized in Table 2.

Table 2. Summary of the effect of the element on far vision.

Element No. 35	Element No. 33	Element No. 32	Element No. 31	Corrected Visual Acuity for Distance in Log units
-0.06	-0.1	-0.1	0.08	-0.08
0.22	0.2	0.16	0.26	0
0.08	0.18	-0.12	0.26	-0.06
0	0.06	0.04	0.24	0.06
-0.02	-0.02	0.04	-0.02	0.04
0.44	0.064	0.004	0.164	-0.08
0.055	-0.064	0.057	0.06	0.03

Note that in contrast to other existing ophthalmic solutions, the presented approach although its performance was quantified only for near and far vision, produces axially continuous focused vision (i.e. fully extended depth of focus).

The subjects of another test group were asked to do some reading. Table 3 presents the results obtained with the EDOF elements while all the tests were taken only with high luminance. Note that the improvement in VA is higher. The improvement appears in various units for convenience. The table also contains the refraction of every subject participating in this experiment.

Table 3. Summary of the reading test.

VA with distance correction (ETDRS Log units, Jaeger and Snellen)	VA with distance correction and EDOF lens	Improvement in Log units	Element No	Refraction	Age
0.6 J8 6/24	0.1 J1 6/7.5	0.5	52 & 51	Myopic -5.00-1.25x76	56
0.62 J8- 6/24-	0.2 J4 6/9.5	0.42	52 & 51	Myopic -2.75	53
0.54 J6- 6/19-	0.12 J1 6/7.5	0.42	51	Myopic -0.5-100x80	65
0.54 J6- 6/19-	0.12 J1 6/7.5	0.42	51	Hyperopic Plan	52

Additional tests that were performed over the test group included:

- 5 subjects were tested monocularly with the "Ishihara" color test, no reduction in performance was found for any of them. Therefore the element preserves color integrity.
- Contrast sensitivity test with Sine Wave Contrast Test (SWCT) of stereo optical co. inc. was performed with 5 subjects. All subjects showed no reduction in performance, or a reduction within the normal range compared to their results with the near vision optical correction.
- Three dimensional capabilities and stereoscopy was tested. No reduction in stereoscopic capabilities was observed.

Here are some definitions of the parameters that we used in order to test and quantify the ophthalmic performance. VA is defined as the resolving power of the eye, or the ability to see two separate objects as separated. Snellen acuity chart includes letters that are constructed so that the width of a stroke equals to the width of a gap. In most Snellen charts, letters are 5 units high and 4 units wide. Visual acuity is specified in terms of the angular size of the gap for the letter with the smallest size that the patient can identify. "Normal" VA is specified as the ability to detect a gap subtending 1 minute of arc. For any target distance, the linear width of the gap  $\chi$  may be determined as follows:

$$\tan \theta = \frac{\chi}{R} \quad (5)$$

Where  $R$  is the distance to the target in meters. For a gap subtending 1 minute of arc and a distance of  $R=6m$  one obtains:

$$\chi = 6m \cdot \tan \theta = 6m \cdot 0.000291 = 0.001746 \text{ m} = 1.746 \text{ mm} \quad (6)$$

For the Snellen fraction (SF) the definition is as follows:

$$SF = \frac{R_T}{R_s} \quad (7)$$

Where  $R_T$  is the testing distance and  $R_s$  is the distance at which the smallest letter that can still be read, subtends an angle of 5' of arc.

The 6/6 acuity standard can be described as a *minimum angle of resolution* (MAR) of 1 min arc. Log MAR is the logarithm at base 10 of the MAR in min arc at viewing distance of

6m. In this system each step is 0.1 log units. The 0.1 'credit' for reading full row of 5 letters can be subdivided into 5 x 0.02 steps for reading each individual letter.

The contrast sensitivity (CS) is defined as:

$$C = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}} \quad (8)$$

Where  $C$  is the contrast. It is computed for a sine wave grating while the spatial frequency is plotted along the x axis and the CS is plotted along the y axis.

Figure 5 presents similar results obtained for elements number 51, 52 and 53 when tested with the same test group. The results in Jaeger units appear in the right part of the plot and are placed there only as a mean of units translation for readers which are more familiar with those units (what appears in the right part corresponds to the units of the left side of the chart). This group of elements is very similar to elements 31, 32, 33, 35. The small differences are in the size of each annular phase structure, the period of its replications (i.e. the distance between two adjacent annular shapes) and its etching depth. In all parameters the variations were only few percentages (about 10) in comparison to parallel values in elements number 31, 32, 33 and 35.

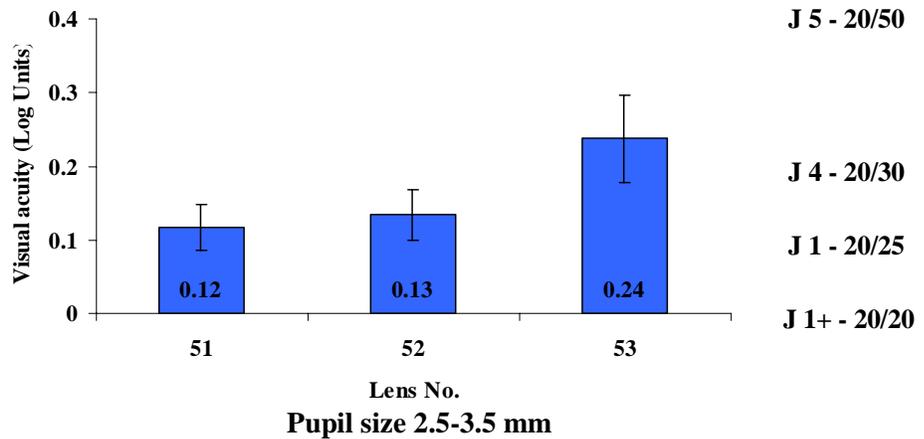


Fig. 5. Visual acuity for near vision obtained over a test group with elements number 51, 52 and 53.

Both elements 31-35 as well as 51-53 included periodic pattern. There was variation of 10% in the period of the replicated pattern as well between the two groups of elements.

### 3.2 Time dependency and field of view testing

The proposed EDOF element has demonstrated performance which is similar to regular spectacles in parameters as the number of Diopters of improvement and the resulted contrast. Additional important parameters that need to be examined as well are related to the field of view at which the EDOF is obtained. This improvement should also be tested as function of time in order to extract the required adaptation time of the brain and its perception. The performed examination is described in Fig. 6.

In Fig. 6(a) and 6(b) we have tested binocular elements (EDOF that was set on both eyes). Figure 6(a) presents the maximal continuous angle of high performance vision where characters are readable successfully in a continuous manner during the readout of this angular region. Figure 6(b) shows the summation of angles, where the patient was able to read successfully a single line of text. For example: assume that a patient is able to read a section of 4 degrees then unable to read a section of 3 degrees and then capable of reading another section of 5 degrees and unable again to read final section of 6 degrees in a line of text.

According to previous definitions, the maximal continuous angle of successful reading will be 5 degrees (Fig. 6(a)) and the summation of angles (Fig. 6(b)) will be 14 degrees.

During the binocular tests, patients were provided with the EDOF elements on both eyes. The patient's head was placed at a distance of 40cm from the printed-paper in an unmovable position and field of view (FOV) measurements were conducted for each eye separately as well as when both eyes are open.

In all experiments in this subsection the EDOF elements were attached on top of the far field correcting lens. The tests took approximately four hours.

The FOV measurements were conducted as follows: paper with printed text was placed at a distance of 40cm from the patient. The text was printed with a functional font size such that each line contained 80 characters constructing a total of 33 degrees in the horizontal FOV (every 2.4 characters occupied approximately 1 degree of the FOV). Every letter was 1.5mm in width and 2mm in height. The separation between letters was 1mm. Test results were treated in a binary fashion: if a patient succeeded reading a character correctly and had no complaints on artifacts, this character was considered to be readable whereas if the patient reported on a double image or a blur, the character was considered to be unreadable. Due to the correction glasses for far field, the subjects saw the entire FOV the same as they see using regular spectacles.

In Fig. 6(c) and 6(d) we performed the same test as in Fig. 6(a) and 6(b) but for monocular element while allowing head movement. Four types of elements were tested in Figs. 6(c) and 6(d): Element number 1 is low density random pattern, element number 2 is periodic and high density pattern, elements number 3 and 4 are elements for sun-glasses application while number 3 is high density periodic pattern and number 4 is low density random pattern. The difference between the low and the high density elements is in the period of the annular shape. Changes of a factor of 2 in the period were performed.

The subjects of the test summarized in Fig. 6 were hyperopic with right eye of +3.00D and left eye +3.50D for far vision and addition of +2.50D for close vision.

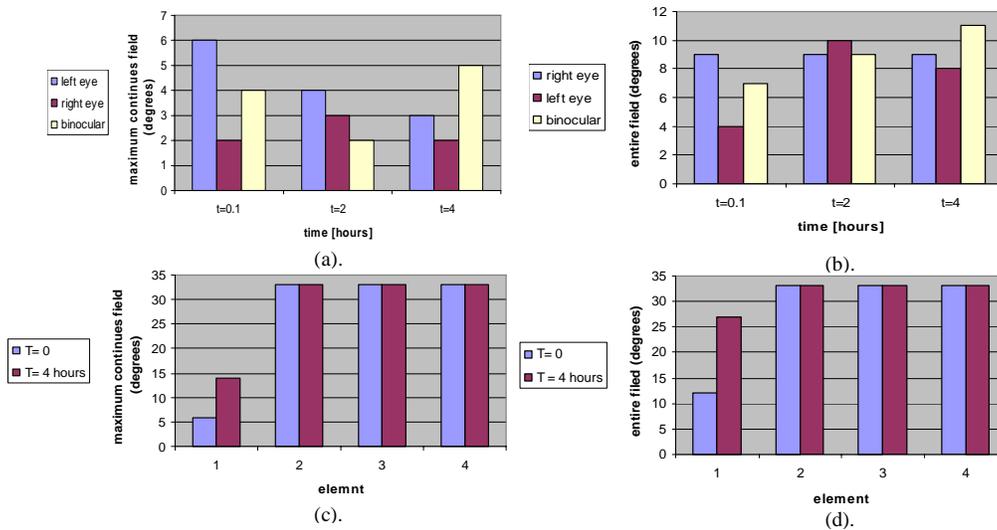


Fig. 6. Time dependency and field of view testing. (a). Maximal continuous field of view versus time for binocular element without allowing head movement. (b). Entire field of view for binocular element. (c)-(d). The same as (a) and (b) but for monocular element while allowing head movement. Element number 1 is low density random pattern, element number 2 is periodic high density pattern, elements number 3 and 4 are elements for sun-glasses application while element 3 is high density periodic pattern and element 4 is low density random pattern.

Note that in the binocular test results when the head movement was allowed the patient read all the text (32 degrees), whereas the far field test result was 6/6. In the contrast sensitivity tests, 5 patients were tested while for all of them the results with the EDOF element were satisfying and all results fall inside the recommended region of the S.W.C.T test chart.

In one binocular test with fixed head an interesting synchronization was achieved between the two eyes such that although right after starting the experiment our subject could read only 2.5 degree of continuous FOV, after 4 hours he managed to see a continuous FOV of 15 degrees.

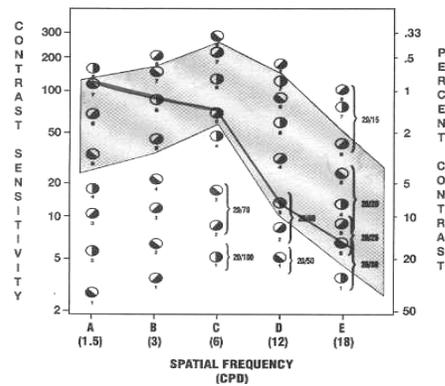
In Fig. 7 we show the S.W.C.T chart and one example of the form filled by one of the subjects of the experiment. The gray region is the region with the range of the normal values. One may see in Fig. 7(b) that the filled values indeed fall inside the recommended gray region.

### S.W.C.T. CONTRAST SENSITIVITY VALUES

R O W	CYCLES PER DEGREE	COLUMN							
		1	2	3	4	5	6	7	8
A	(1.5)	3	6	11	18	33	65	110	150
B	(3)	4	8	13	23	42	85	155	195
C	(6)	5	10	19	42	65	120	180	240
D	(12)	5	8	14	30	52	90	120	155
E	(18)	4	7	10	14	24	37	68	95

(a).

### SINE WAVE CONTRAST TEST (S.W.C.T.) RECORD FORM



(b).

Fig. 7. S.W.C.T contrast sensitivity values chart and one example form that was filled by one subject of the experiment. The gray region is the region with the normal values range. One may see in Fig. 7(b) that the filled values fall inside the gray region.

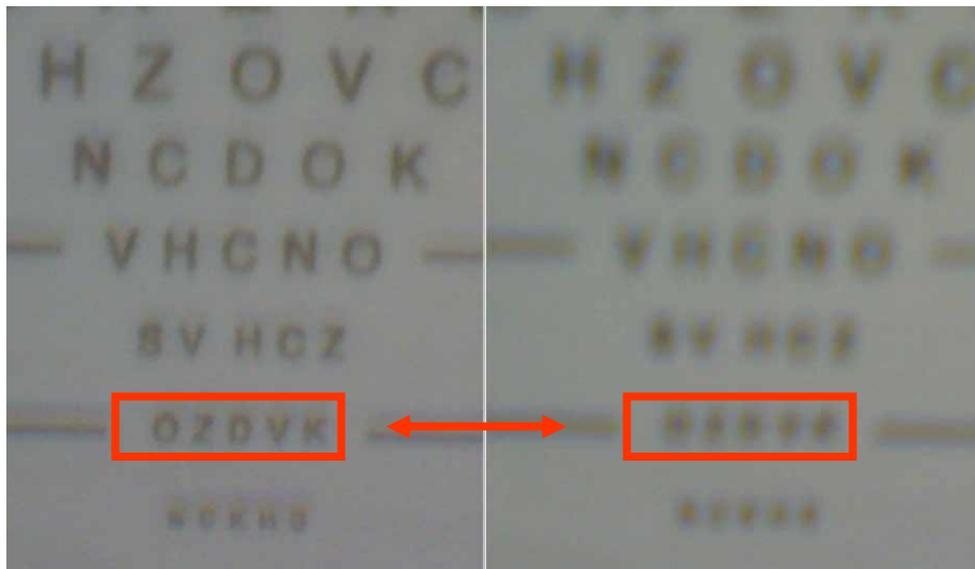
### 3.3 Astigmatism

Astigmatism is an optical defect in which one or more of the refractive surface of the eye is toroidal rather than spherical in its shape. As a result, the refracting power in regular astigmatism is different in various meridians, with the meridians of maximum and minimum powers (referred to as the axes of the astigmatism) at right angles to each other. In such a system, a distant point object has two focal lines parallel to the meridians of the maximum and minimum power, thus a point of focus is never formed.

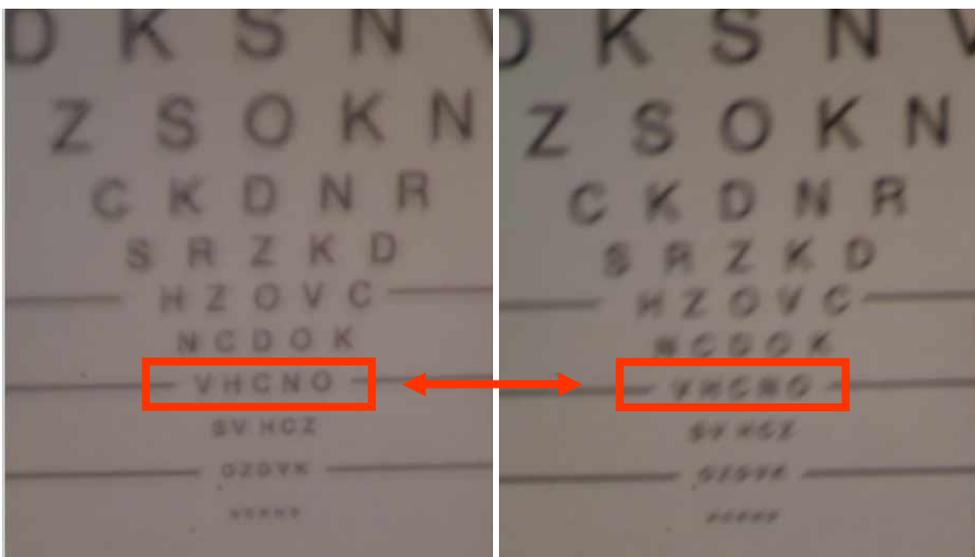
When the two principle meridians are orthogonal, the astigmatism is defined as regular; when the axis between the two is different the astigmatism is defined as irregular. At this time there is no available solution for irregular astigmatism with goggles and it can only be corrected by contact lenses. In this subsection we aim to show that our EDOF element is suitable for correcting both types of astigmatism, regular as well as irregular.

Figure 8 presents the obtained experimental results. In Fig. 8(a) we present the results for irregular astigmatism where the left part is the result that is obtained with the EDOF element and the right part is obtained without it. Figure 8(b) presents the experimental results obtained for regular astigmatism. Once again the left part of the image is obtained with the EDOF element and the right part is captured without it. In both cases one may clearly see the significant improvement that was obtained with the EDOF element. This improvement is equivalent to 1.50-2.00D (each line of improvement in the ophthalmic resolution chart is 0.5

Diopters in the case of astigmatism). In order to emphasize the significant improvement we marked the line in the resolution chart having the smallest letters that are still readable (therefore there the improvement is mostly evident) by red rectangle.



(a).



(b).

Fig. 8. Experimental results for: (a). Irregular astigmatism. (b). Regular astigmatism. In both cases left part is the result that is obtained with the EDOF element and the right part is obtained without it.

In Fig. 9 we have tested the presented EDOF concept for astigmatism over a test group of 5 people. The chart is the chart of VA while the dark lines represent the standard deviation for each measurement. The left column represent the VA for far vision subjects after being corrected with regular glasses. The central column is the VA obtained after an addition of a cylindrical lens of 2 Diopters (it is equivalent to 1 Diopter in spherical lenses) that was added

on top of the correction spherical lens. Indeed the VA was destroyed by 2 Diopters. In the right column we have added the EDOF element on top of the cylindrical lens. One may see that the VA was restored to be the initial and intact value displayed in the left column.

### +2.00 D. Astigmatism

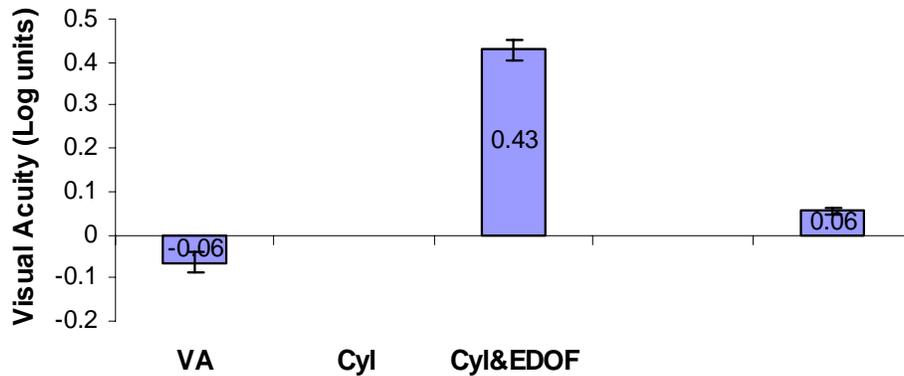


Fig. 9. Test group for astigmatism treatment characterization.

#### 4. Conclusions

In this paper we have presented the adaptation of an all-optical extended depth of focus approach that was developed for digital imaging, to the ophthalmic field of applications. The development was done for spectacles while the obtained results included improvement of up to 3 Diopters for eye pupil diameters of 2-4mm. The main application for the device developed in this paper is related to people that are requiring bifocal solutions. Additional work is currently conducted on elements having larger extended depth of focus capabilities suitable for larger refractive error.

The presented technology was also demonstrated as possible solution for regular and irregular astigmatism. Improvement of 2 Diopters was demonstrated. For both applications the developed technology was tested experimentally as well as over small test group.

The main advantage of the developed optical element which also looks cosmetically acceptable, is that it is very thin (less than few microns) and has low price, it has high energetic throughput and low chromatic aberrations and it operates over the full field of view while providing axially continuously focused image (in contrast to bifocal lenses having only 2 focused regions) with simultaneous solution for regular and irregular astigmatism (for irregular astigmatism currently no spectacles based solution is available).