Optics Communications 319 (2014) 113–116

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Multifocal rigid gas permeable contact lenses with reduced halo

Shai ben Yaish [a], Alex Zlotnik [b], Ofer Limon [b], Karen Lahav Yacouel [b], Ravid Doron [b], Zeev Zalevsky [a,*]

[a] Faculty of Engineering, Bar-Ilan University, Ramat-Gan 52900, Israel
[b] Xceed Imaging Ltd, 20 Hamagshimin St., Petach-Tikva, Israel

ARTICLE INFO

Article history:
Received 27 October 2013
Received in revised form
10 December 2013
Accepted 5 January 2014
Available online 20 January 2014

Keywords:
Contact lens
Multi focus
RGP lens

ABSTRACT

In this communication we present the first dispensing medical trial in which we successfully report on testing of novel extended depth of focus rigid gas permeable (RGP) contact lenses having reduced halo and distinct focal peaks for near and far distance vision.

1. Introduction

The purpose of this study is to present extended depth of focus (EDOF) rigid gas permeable (RGP) contact lenses with reduced halo and distinct near and far focal peaks. These lenses will aid in solving presbyopia, while providing better image quality than current RGP contact lenses available in the market.

The lenses feature laterally large (tens of wavelengths) concentric scratches of depth of less than one micron on top of a regular RGP rigid contact lens. Through these, an axially extended point spread function is generated at the focal spot of the lens. By avoiding radial discontinuity in the scratches the halo effect (which is generated around bright points when being imaged by the lens in low light illumination conditions) is significantly suppressed.

In this paper we have fabricated our EDOF rigid contact lenses and tested them both on an optical bench constructed according to the Arizona eye model [1] as well as in clinical trials including dispensing experiments with 10 patients. The performance of the proposed lens was compared to existing multifocal aspheric RGP lens and significant improvement in performance was demonstrated.

Currently there are two types of multi focal technologies in RGP contact lenses. The first is aspheric lenses [2–4] which is the more common solution. The asphericity of the lens creates a continuous through focus modulation transfer function's (MTF) extension. However, it produces low image quality, along with low contrast and significant halo effects in low light illumination conditions. The second solution is related to refractive lenses which include rings with different focal lengths generated on top of the rigid contact lens [4–9]. Similarly to the aspheric designs, this solution also results in low image quality performance and suffers from strong halo effects in low light illumination conditions.

In this paper we propose a new EDOF technology based upon interference effect [10–12] which was developed in Xceed Imaging, Ltd. This technology was demonstrated and documented previously in soft contact lenses [12]. The current paper highlights the benefits of the EDOF technology in RGP contact lenses. The two primary advantages are: good contrast performance for both near and distance vision (thus they can be very applicable for treating prebyopia), along with reduced halo effect. The latter is achieved by breaking any radial discontinuities in the concentric scratches, leading to a proper axially extended point spread function due to interference.

2. Fabrication

The EDOF RGP contact lenses have been fabricated as can be seen in Fig. 1. Fig. 1(a) and (b) illustrates the scanning electron microscope (SEM) images of the EDOF pattern, clearly revealing the large annulars which cause the desired interference EDOF effect. The engraved annulars are marked with black arrows on top of Fig. 1(a). In Fig. 1(b) one may see a zoomed image of one of the annulars which is also marked with black arrows on top of the figure.

Fig. 1(c) exhibits the contact lens with the EDOF element as viewed with slit lamp using fluorescein (in vivo). In the front view of the contact lens of Fig. 1(c) one may again see the EDOF annulars.

* Corresponding author. Tel.: +972 35317055.
E-mail address: zalevsz@biu.ac.il (Z. Zalevsky).

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http://dx.doi.org/10.1016/j.optcom.2014.01.011

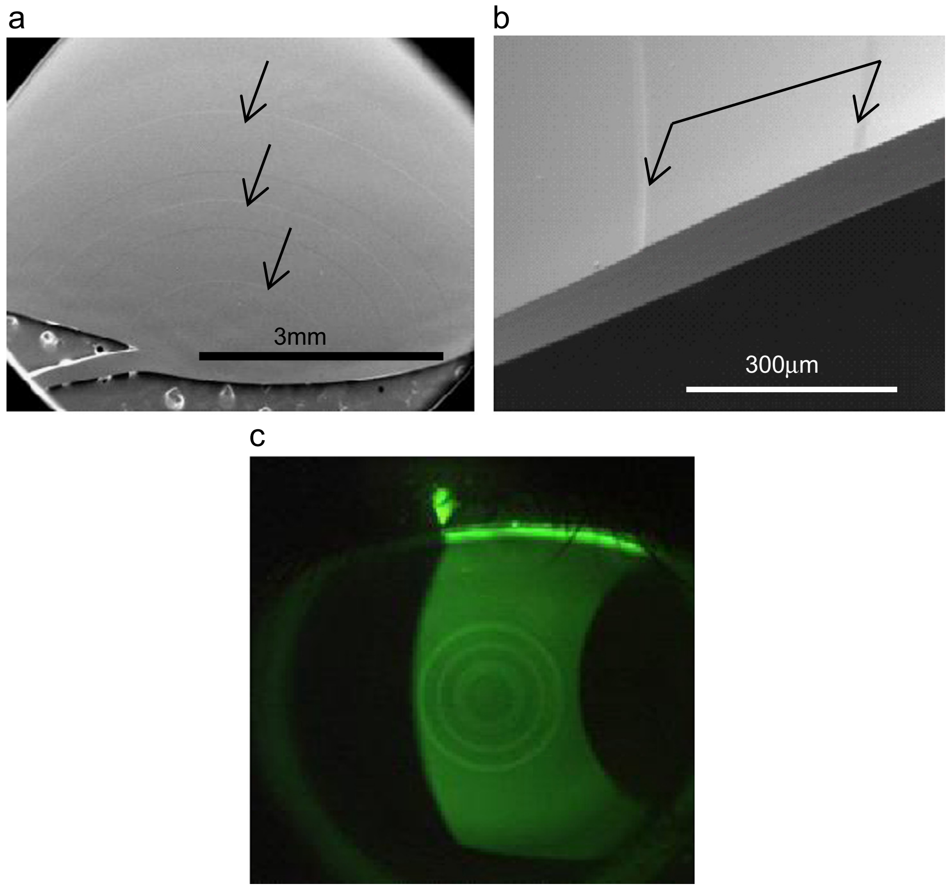

Fig. 1. The characteristic features of the EDOF contact lenses (a), (b) SEM image of the pattern. (c) Image from in-vivo observation with slit lamp using fluorescence.

3. Optical bench testing

Initial results include bench images, using the Arizona eye model. The optical bench featured in Fig. 2(a), includes computerized stages and lenses simulating the lenses of the human eye, light source and a camera. In the upper part of Fig. 2(a) one may see the image of the optical bench with arrows pointing out to each one of the optical elements in the setup. In the lower part of the figure one may see the schematic sketch of the optical configuration.

The bench pictures in Fig. 2(b) feature the distance field images on the left column, and the near field images on the right column. On the upper line of Fig. 2(b) are the images obtained for a monofocal lens which provides a good distance field image but a very defocused near field image. The second line is the result obtained with an aspheric RGP lenses aiming to provide both good near and far imaging. It is seen that although some focusing is visible, the image quality is very low and features high aberrations. The third and forth lines are the results obtained with two different interference based EDOF designs that we realized. In both cases the near as well as the far images are sharp and they produce significantly better results than the competing aspheric RGP lenses.

In Fig. 2(c), we illustrate the through focus MTF charts (those are charts plotting the contrast for specific spatial frequency versus the axial position of the imaged object that is being measured in units of Diopters. If the depth of focus is e.g. extended by 3 Diopters, no residual accommodation capability will be required) for the aspheric RGP lenses followed by the two EDOF designs that we realized. The better quality visual images of Fig. 2(b) are evidenced in a quantified way in the through focus MTF charts showing significantly higher contrasts for both near and far distance vision.

The results show significantly better image quality including more than 5 lines of improvement in resolution in the USAF resolution target object, in respect to the aspheric RGP lenses. Using the EDOF lenses, at a spatial frequency of 100 cycles/mm, 65% and 30% contrast was obtained for the distance and near vision respectively. In comparison, 20% contrast and below, was the result with the aspheric RGP, at the same spatial frequency, for both distances.

One of the main advantages of the proposed EDOF design is the capability to reduce the hallo effect which is very apparent and dominant in diffractive lenses. Fig. 3 represents some experimental results obtained from our optical bench. The images in Fig. 3 are displayed in logarithmic scale. The images from the left to the right are related to imaging of a point light source for a monofocal design, an EDOF design and an aspheric design respectively. It can be seen that the hallo of the EDOF lens is similar to the monofocal lens, both being very small, featuring the point source as a sharp point. In the aspheric lenses the point is surrounded with a large circle causing a hallo embedded reduced image quality. This is of high relevance when using the contact lenses in a dark environment such as at night time.

4. Clinical dispensing trials

The results of the clinical trials performed with the proposed interference based EDOF lenses are seen in Fig. 4. The lenses were trialed in a dispensing experiment, where 10 subjects (5 males and 5 females at average age of 55 with standard deviation of 9.3 years) were appropriately fitted with the lenses and wore them for a trial period of a month. The lenses achieved good repeatable results, with high predictability of success on the first visit (results were