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Lens surface roughening for tears invariant contact lens performance

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ABSTRACT

In many extended depth of focus diffractive or interferometry based ophthalmic contact lenses the time varied tears layers affect the ophthalmic functionality of the lens. In this paper we present a new approach involving nano pillars realized inside the grooves of a contact lens aiming to implement any type of extended depth of focus or diffractive optical element for ophthalmic applications in order to solve the micro fluidics layer uncertainty within the micro sag features.

1. Introduction

Recent technology involving extended depth of focus (EDOF) for ophthalmic applications uses annular grooves across a standard lens to create a proper phase retardation that leads to an interference pattern along the focal distance and when controlled properly can provide an EDOF outcome that is useful for correcting a very common ophthalmic problem such as presbyopia [1,2]. Other techniques are presenting diffractive optical elements that can diffract the optical signal into different diffraction orders realizing a bi-focal or multi-focal lens [3–6] that allow a clear vision for different object's distances using a passive single lens. Both the diffractive as well as the above mentioned interference EDOF technology implement their phase reshaping by introducing usually annular grooves along the plane of the lens, that produce the required phase retardation in the focal plane. To maintain an accurate phase reshaping one has to control the refractive index difference between the lens and its surroundings with high precision. When involving a liquid environment, such as tears in ophthalmic applications, there is a great uncertainty regarding the exact phase that the optical element can introduce as the tears layer filling the grooves of the lens changes the relative refractive index difference between the lens and its surrounding. This uncertainty changes the ophthalmic functionality and damages the EDOF performance.

In this paper we propose a new concept in which nano pillars are generated inside the original grooves that are responsible for the photonic functionality of the contact lens [7,8]. The nano pillars do not affect the phase retardation that the original large grooves aimed to produce the photonic EDOF functionality but they inhibit any micro fluidics movement within the optical element and as their dimensions are sub wavelength they produces no diffraction effects [9].

2. Optical design

Several attempts have shown a binary grating structure that realizes a graded index grating [10]. In order to produce a constant phase shift we generate nano pillars inside the etched region (which in our case are the annular grooves causing the EDOF effect). Those pillars should be denser than the optical wavelength in order to prevent generation of undesired diffraction orders [9]. The etching depth of the annular will also be computed differently following the equation below [11]:

$$\delta=\frac{\Delta\varphi_d\lambda_0}{2\pi(n-n_{eff})}\quad n_{eff}=\frac{\Delta x\times M\times n+(L-\Delta x\times M)}{L} \tag{1}$$

where δ is the needed etching depth, λ_0 is the nominal illumination wavelength, Δx is the average width of the pillars, M is the number of pillars inside the annular groove, L is the lateral width of the annular and $\Delta\varphi_d$ is the phase retardation that we aim to generate with the annular. n is the refractive index of the pillar and n_{eff} is the effective refraction index of the groove due to the addition of the pillars. The schematic sketch of the proposed configuration is presented in Fig. 1.

Generation of nano adjacent pillars will create a surface tension that is much higher than the pressure of the fluids, hence will maintain a steady state environment inside the grooves. Two possible configurations are considered while in both uniform ophthalmic performance is to be obtained versus time without dependence on the temporal changes in the tears layer:

- No fluids penetrate into the groove structure in a hydrophobic material of the contact lens.

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- Fluids fill constantly the gap between the nano grooves in a hydrophilic material.

The presented simulations assume a hydrophilic material.

3. Simulations

In order to solve accurately the sub-wavelength structure we used Comsol Multiphysics to solve the Maxwell wave equation via the final element method. The illumination is a normally incident TE polarization plane wave and the wavelength is 550 nm in free

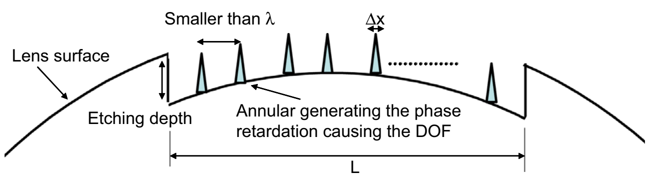

Fig. 1. Schematic sketch of the proposed element.

space. We designed a reference phase delay retardation groove with width of 300 μm and etching depth that generates phase retardation of π:

$$\delta = \frac{\lambda_0}{2\Delta n} \tag{2}$$

where Δn is the difference between the foreground (groove surrounding) and background (groove) refractive index and λ_0 is the free space wavelength. Using BK7 with refraction index of 1.517 as foreground and water with refraction index of 1.3 as background the etch depth was found to be 1.267 μm. The total width of the simulation was done for width of 0.8 mm and for axial length of 3.5 μm. One can verify in Fig. 2 that the phase difference between the groove and its surrounding is being linearly accumulated along the groove until it reaches π at the end of the element. The units in Figs. 2–4 are in meters.

In Fig. 3 the refractive index of the nano pillars structure is depicted. We designed a 300 nm period structure with duty cycle of 33.3% (i.e. 100 nm foreground and 200 nm background) that implements the same reference groove. In order to reach the same phase shift we changed the nano pillars length and the etching

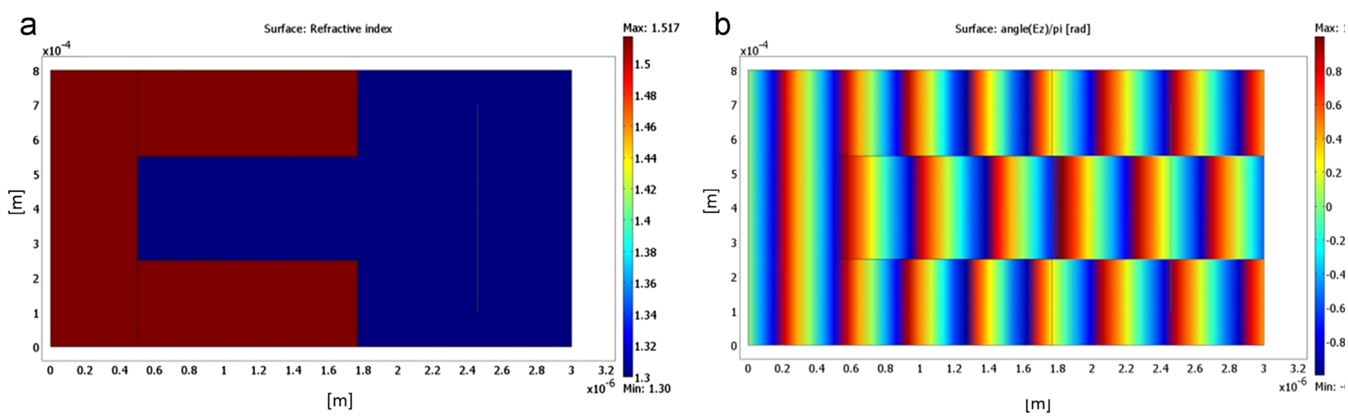

Fig. 2. Reference micro groove generated in BK7 and implementing a phase retardation of π. (a) Refractive index of the suggested design. BK7 material (refractive index of $n=1.517$) is presented in red, water (refractive index of $n=1.3$) is presented in blue. (b) Phase distribution of the perpendicular electric field obtained along the phase plate shifter. A phase delay of π is generated after propagation in a groove with etching depth of 1.267 μm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

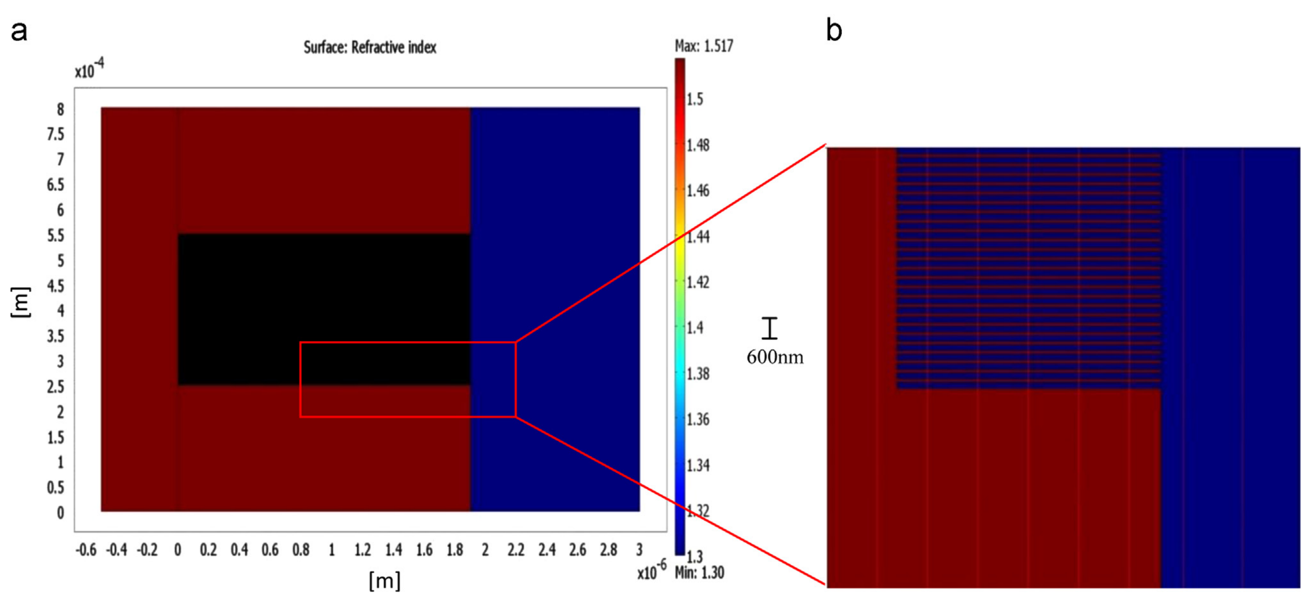

Fig. 3. Refractive index of periodic nano pillars generated inside an EDOF groove realizing a π phase shift. (a) Overview of the device. The black region presents the 1000 periods of nano grooves. (b) A close-up into the groove area. Multiple pillars with period of 300 nm where the ratio between the BK7 material and water is 1:2.