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Retina-simulating phantom produced by photolithography

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Cone photoreceptors have a narrow acceptance angle well matched to the size of the eye pupil that dampens the visual impact of aberrations and scattering. However, the structure of the human retina is not replicated in existing eye models used to test refractive designs or retinal implants that restore partial vision to the blind. Here, we report on an artificial waveguide-based retinal phantom manufactured by photolithography in photoresist film with dimensions and refractive index contrast similar to the retinal receptor layer. The optical performance of the waveguide array is analysed in terms of angular coupling efficiency and it is experimentally verified that the structure leads to improved resolution and contrast of optical images transmitted through the layer when defocus is present. © 2017 Optical Society of America

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The photoreceptors of the human retina are elongated cells endowed with directional sensitivity, having a lower visual response to obliquely oriented incident light, as described by the Stiles-Crawford effect of the first kind (SCE-I) [1]. This selectivity operates as a low-pass angular filter that dampens the influence of outer parts of the pupil, associated with larger wavefront aberrations and reduces the impact on vision of intraocular scattering of light.

However, this effect is not included in refractive eye models that mimic the anterior eye using a lens or combination of lenses and a CCD camera or a screen in the retinal image plane when estimating effective retinal images. The photoreceptor morphology and packing is also ignored in current retinal implants. These are based on photosensitive surfaces that electrically stimulate the inner retinal layer and ganglion cells and bypass deteriorated photoreceptors [2, 3]. Those photosensitive surfaces are responsive to light being incident at a wide range of angles without discrimination and therefore fail to dampen oblique light. The visual performance of current implant technology is also limited by the small number of pixels but it is expected that future implants will have an increased density of active elements where the add-on of a physical retinal model can become beneficial.

The SCE-I is commonly expressed by [4]:

\[ \eta(r) = 10^{-7} r^2 \]

where \( \eta \) is the relative visibility, \( r \) is the characteristic directionality parameter and \( r \) is the distance in the pupil from the peak of visibility or, with respect to the incident angle at the retina; \( r = \theta f_{eye} \), with \( f_{eye} = 22.2 \text{mm} \) for a schematic eye model. Therefore, light at larger angles contributes negligibly to vision. For a typical directionality of 0.05/\( \text{mm}^2 \) this dampens obliquely light to an effective pupil size of \( d_{eff} \approx 6 \text{mm} \).

The Gaussian dependence is similar to the coupling efficiency of single-mode optical fibers [6, 7]. Here, a waveguide based retinal phantom is proposed to improve refractive eye models and, potentially, retinal implants. Waveguide arrays are commonly used in fiber-optic endoscopes to transport light and images from one location to another and tapered waveguide arrays have been used as magnifiers for people with vision impairment [8]. Waveguide arrays have also been proposed as photoreceptor simulators at microwave [9] and optical frequencies [10]. Here, it is the first time that structural dimensions have been made comparable to actual retinal photoreceptors and tested with respect to directionality and angular filtering on imaging.

![Fig. 1.](a) Top view sketch of the chrome mask used for photolithography. The UV light is transmitted through the gray circles, reaching the photoreisit in hard contact with the mask; (b) Lateral view sketch of the UV exposed areas of the photoresist; (c) Optical transmission image of the photoresist after post-exposure baking illuminated by white light. The printed array of cylinders operates as an array of waveguides, simulating the photoreceptors directional sensitivity at the retina.)
The simulator consist of an array of dielectric cylinders manufactured by photolithography using photoresist AZ40XT (Microchemicals GmbH ™) [Fig.1]. This positive photoresist presents good adhesion to the substrate and suitable film thickness via single spin-coating with thickness controlled by spin speed. Chemical amplification improves the photosensitivity of this material allowing high spatial resolution [11], which makes it suitable for fabrications that require high aspect ratios.

The photoresist was deposited onto a silica cover slip. To avoid contaminants and improve film adhesion, the substrate was pretreated with acetone cleaning and distilled water rinse followed by baking at 200 °C for 10 minutes to dehydrate the surface. After spin-coating, the AZ40XT was soft-baked at 125 °C for 15 minutes to remove the solvents. Contact printing was then performed to obtain the cylindrical structures by illuminating through a chrome photomask overlaying the photoresist with a collimated beam of UV light (365 nm, 300 mJ/cm²). The photomask had a hexagonal lattice of 5 µm circles separated by 10 µm [Fig.1(a)], similar to the distribution of retinal cones in the vicinity of the fovea [12]. The dimensions and packing can easily be altered with alternative mask configurations. Finally, the photoresist was baked again at 105 °C during 15 minutes to catalytically perform and complete the photoreaction initiated during exposure. Both soft-baking and post-exposure baking were performed in temperature steps of 25 °C every 5 minutes to avoid bubble formation and the film was cooled slowly to avoid thermal shock and potential cracks. The processed resist had a thickness of 50 µm and a latent image was formed by the diffusion of photosensitive catalysts indicating index contrast between exposed and non-exposed areas [Fig.1(b)]. Conventional post-exposure chemical etching of the photoresist is not required in this experiment.

![Schematic of the interferometric setup and sample preparation](image)

**Fig. 2.** Beam splitter, Objective: Olympus UPlan 20X, λ = 543 nm, L = 200 mm. L2 of two interfering plane waves was used to measure changes in the refractive index of photoresist exposed to UV light.

![Interference patterns](image)

**Fig. 3.** (a) Interference pattern observed by the Mach–Zehnder interferometer in presence of the photoresist. Zoom-in at the lower-left corner; (b) interference pattern simulated using the MatLab software. Zoom-in at the lower-left corner.

The refractive index variation was estimated using a Mach–Zehnder interferometer schematically represented in Fig.2. A HeNe laser beam (543 nm, cw) is split into two: the first goes through the photoresist sample and is imaged by a CCD camera connected to a microscope; the second is expanded by a telescope and incident on the camera at an angle to form an interference pattern. The difference of refractive indices between UV exposed and non-exposed areas results in local distortion of the fringes [Fig.3]. This bending was analysed using the software MatLab™, and a maximum increment of ∆n = 0.004 was estimated in the areas exposed to the UV. The higher refractive index enables each cylindrical column in the ensemble to operate as an independent waveguide.

To analyse the coupling efficiency and sensitivity of this structure to obliqueness of incident light, the second branch of the interferometer was removed. Photoresist, microscope and CCD camera were mounted onto a rotation stage, centered at the photoresist, to control the incident angle at the sample. It is possible to observe that light transmission decreases with increased angle of incidence [Fig.4]. The average transmitted power through the cylinders has been fitted to the Stiles-Crawford function and the directional parameter estimated as

\[
\rho = 0.016/m^2
\]

for a schematic eye model [Fig.5]. This is smaller than for foveal cones but potentially modifiable with other resists and/or dimensions [13].

The guided modes of an optical fiber are formed by total internal reflection (TIR) at the core, causing light rays to self-

![Experimental analysis](image)

**Fig. 5.** Experimental analysis of the average transmitted power data. Best fit of the Stiles-Crawford effect with \( \rho = 0.016/m^2 \) line.
interfere. However, the short propagation distance would not allow the radiation modes to be properly dissipated. As a result, a combination of guided and non-guided light is measured at the exit of the waveguides, reducing its effective directivity.

The dependence on length of the refractive-index-enhanced cylinders (L) in a hexagonal infinite lattice was analysed using the software Comsol Multiphysics™. The simulations were performed in 3D, assuming the same refractive indices, geometry and distribution as in the photoresist. The results are presented in Fig. 6.

For $L < 50 \mu m$ the light distribution across the array does not indicate a proper confinement of light at the core. Above it, a single mode profile becomes perceptible. The desired decoupling between guided and radiative modes corresponds to an increasingly narrow distribution of transmitted light through the high-index cylinders. The distributions have been fitted to the Stiles-Crawford function at small angles showing a sigmoidal growth of the directional sensitivity as a function of waveguide length.

At larger angles ($\Theta > 6.5^\circ$) the wave is incident above the acceptance angle and the light is no longer guided. However, due to the short distances and the transparency of the film, the light radiate through neighboring cylinders [Fig.4], with a resemblance to the images of the layered scattering model of the outer segment, that does not rely on waveguiding properties of the photoreceptors [14]. This effect could be related also to the photoreceptors in human retina, playing a role for the Stiles-Crawford effect of the second kind (SCE-II) [5, 15, 16], referred to as the effect of hue shift observed when monochromatic light intersects the retina at different angles [4].

The leakage to neighboring cylinders could be avoided by the introduction of an absorber in the cladding, that would assist the dissipation of the radiant modes and increase the directionality further. For a 50$\mu m$ long array in the presence of an absorption (at $\lambda = 532\pm 5\mu m$), the directional sensitivity was analysed with different aberration conditions. The effective images were created to analyse just the light that goes through the cylinders, without printed cylinders. In the presence of printed cylinders, the position of each of them was detected using Matlab™ and a mask function was created to analyse just the light that goes through the high-index cylinders. The presence of absorption in the surrounding cladding would eliminate the needing of the mask function. Furthermore, a set of images shifted gradually in the $xy$ plane are digitally combined to fill the gaps between the waveguides. That shifting would, in the human eye, be accomplished by tremor and saccades. The same mask and shifts were also applied to the images without the cylinders for an equitable comparison. The effective images were analyzed with different aberration conditions, generated by the displacement of $L_1$ on axis with respect to the best focal plane.

As shown in Fig. 8, no appreciable difference is observed between the images obtained with or without printed cylinders when the target is in focus (planar wavefront). However, in the presence of defocus, the curvature of the wavefront results in a reduction of the coupled light by the printed cylinders, proportionally to the local wavefront tilts at their entrance, for

![Fig. 6. Comsol™ modeling of an infinite periodic array of hexagonal lattice, with refractive indices 1.591, 1.593, 1.595, at $L$ values of length from 10$\mu m$ to 100$\mu m$. (b) Transmitted power fraction through the cores as a function of angle of incidence; (c) Directional sensitivity as a function of waveguide length.](image)

![Fig. 7. Setup (not to scale) to analyze the influence of the photoresist operating as an angular low-pass filter on the image quality. The lens $L_1$ is mounted in a translation stage to controllably induce defocus in the wavefront. $L_1 = 19mm$, $L_2 = 150mm$, objective Olympus UPLAN 20X, Iris $\Phi = 6mm$.](image)
The image filtering would be even more pronounced with a retinal phantom having \( \rho \). The potential enhancement of contrast and resolution was simulated using Matlab™ with \( L_1 \).
FULL REFERENCES