Compact See-though Near to Eye Display with Diffractive Optical Elements

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Abstract

The Near to Eye Display (NED) solves the problem of having a display larger than a small portable device. The virtual image of the NED is created using a microdisplay and imaging optics. It is important that the optics does not interfere with the human visual system and that the device is light, compact and easy to wear. In this paper the principles of a biocular NED, which is based on a novel diffractive Exit Pupil Expander (EPE), are presented. The optical system is compact and intrinsically free from distortions and misalignments.

1. Introduction

The increased speed of wireless communication enables the users to enjoy the videos and multimedia while in motion. On the other hand, the size of the display of a mobile device itself is rather small and is a limitation for example for browsing videos. One method to overcome this problem is to use Near to Eye Displays (NED). In these display terminals the challenges are in achieving low power consumption and small weight and size. Typically these devices are mounted someway to the head and they cannot be too heavy. The face worn displays that rely on the support of the nose should weight less than 100g, or even less than 50g. The trend clearly is towards very light devices and their optics has a major role in reducing the volume and weight. Another important aspect besides the weight is that a display for both eyes, i.e. biocular, is more comfortable and creates less health issues than a monocular one [1, 2]. Here we shall consider only the biocular systems. The comfortableness is related to the quality of displays, optics, alignment tolerances in manufacturing, and accuracy of installation on the head.

The type of microdisplay influences the size of the optics slightly, but even scanning system needs optics of about the same size as any other microdisplay. There are myriad types of optical methods to create images from a microdisplay to the eyes of an observer [3]. Here we are going to present a NED based on Exit Pupil Expander (EPE) that is realized using diffractive optics on a planar waveguide [4]. In this system there is only one microdisplay and one optical engine to produce images for both eyes, as shown in Fig. 1.

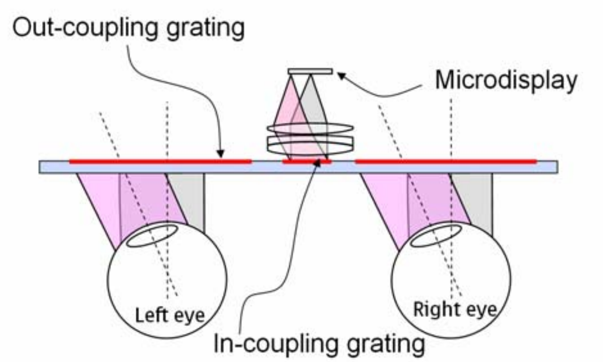

Fig. 1. Top view of the optical setup of a NED based on a straight diffractive EPE.

The efficiency of the out-coupling grating increases gradually towards the end the plate and is almost everywhere less than 20%. Due to the transparency of the EPE plate the NED is a see-through system.

The parallelism of the surfaces of the EPE must be typically better than one arc minute in order not to experience any chromatic aberration. There is also a tight tolerance for the surface flatness but this and the parallelism requirement can be met reasonably well with traditional optical manufacturing. The diffractive EPE plate itself has an infinite focal distance and the focal distance of the Optical Engine (OE) must also be infinite. The optical engine can also be in the same side as the observer, but then EPE plate performs like a mirror and the image must be corrected accordingly in the microdisplay.

The recent developments in grating manufacturing have removed one of the obstacles in the technology, the low efficiency of the gratings [5]. The use of slanted gratings enables some new features, because the EPE can be split in two parts along the centerline of the in-coupling grating. These left and right EPE's are independent from each other. The EPE plate can then be tilted in an angle [6], as shown in Fig. 2. This arrangement gives a new design freedom.

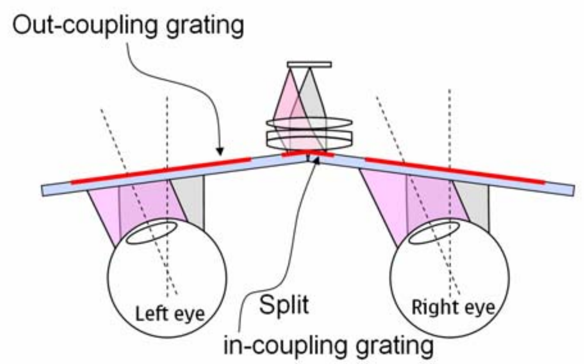

Fig. 2. Top view of the optical setup of a NED based on a split diffractive EPE system tilted in a chevron configuration.

One should remind here that the required optical accuracy of the chevron system is easier to achieve if the optical engine is at the different side of the plate as the observer.

Therefore, the positioning, tilting or rotating of the EPE plates is possible without affecting the quality of perceived image. Generally the slanting angle of the in and out-coupling gratings must be higher than in the straight EPE case. The practical maximum value for the chevron angle (between the normal of the plates) is about 40 degrees. This limitation is due to the drop of the incoupling efficiency at large angles.

2. Horizontal expansion of the exit pupil

The slanting of the gratings improves many features in the EPE but cannot hail the general malicious behavior of the light distribution at the output in the horizontal direction [4]. The uneven distribution is mainly due to the different distances between the Total Internal Reflections (TIR) of the trapped light inside the plate as shown in the Fig. 3. The short TIR distance means that the light is collected out from the plate too quickly and the intensity is concentrated to the side of the out-coupling grating that is closest to the in-coupling grating. The longer TIR distance concentrates the light at the end of the plate.

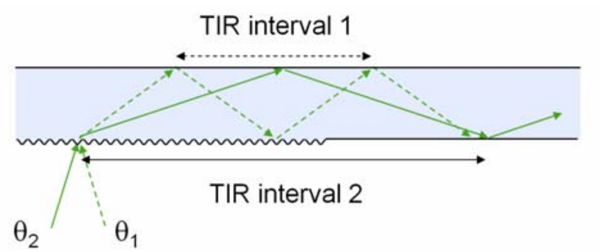

Fig. 3. The TIR distance depends on the incoupling angle.

There is also an angular dependency of the diffraction efficiencies but the TIR distance dominates the out-coupling behavior. The light distribution is opposite to what one would desire, as shown in Fig. 4., and much of the light is wasted.

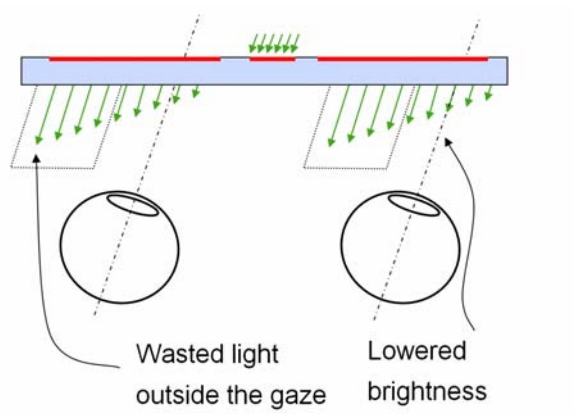

Fig. 4. Intensity distribution in a diffractive EPE plate at the edge of Field of View. The light intensity is weakest at the gaze direction.

The light distribution can be redesigned with a thin layer of a low refractive index material inside the plate. The principle of operation is that this layer homogenizes the distance between two TIR's inside the plate. The extreme angles either are reflected or transmitted through the interface, The TIR distances of the angles between the extremes are statistically about the same as the TIR distances of extreme angels. Some light is permanently trapped in the upper layer but its amount is very small compared to the gain achieved in this configuration.

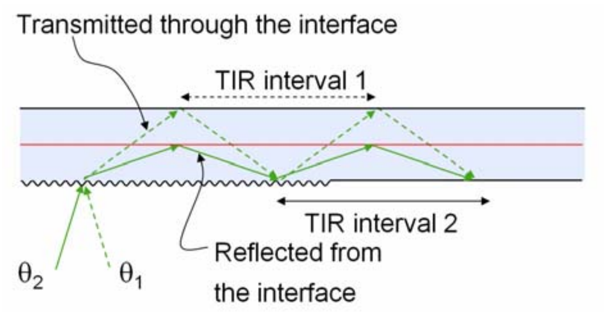

Fig. 3. The TIR distance is equalized by a thin film layer of a low refractive index material.

The distribution of the light at the output aperture is more uniform and in fact it can be even tailored to favor more the gaze direction, as shown in Fig. 6. The total amount of the light entering into the eye is drastically increased.

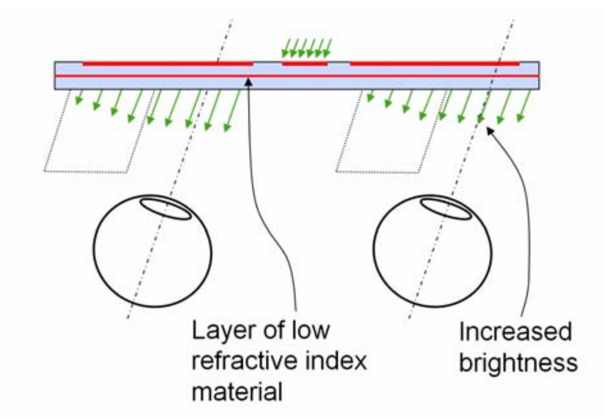

Fig. 6. Intensity distribution in a diffractive EPE plate at the edge of Field of View. The light intensity is weakest at the gaze direction.

The diffraction angle depends on wavelength. The longer wavelength diffracts the light to larger angles compared to shorter wavelengths. Therefore there is an intensity of light at the output is not uniform. This is one of the most pronounced and disturbing feature of the EPE based VRD. Fortunately the thin film solution improves drastically also the color balance of the system. This is well understood with the equalized TIR intervals.

3. Vertical expansion of the exit pupil

The exit pupil can be expanded also in the vertical direction as described in references 7 and 4. There are at least two different categories of vertical expansion methods. They are based on even or odd number of first order diffractions in an intermediate grating that is located between the in-coupling and the out-coupling gratings. The method based on odd number diffractions suffers from large polarization dependence and low efficiency. The method based on even number of diffractions is almost polarization independent but suffers from beam detorioration due to multiple diffractions. In this paper a new vertical expansion method is presented that is more accurate and more efficient than any other method. It is based on a novel layout of the gratings of the even type vertical expansion.

The method of even number of diffractions works optimally with gratings that are oriented at 60 degree conical angle with respect to the incoupling one. The grating periods are the same as incoupling grating which facilitates the experimental work. The basic principle is to minimize the number of first order diffractions, *i.e.* to have only two diffractions. Another consideration is that the light should be guided towards the gaze direction. Therefore we divided the expanding grating in two areas each having only one first order diffraction, as shown in Fig. 7.

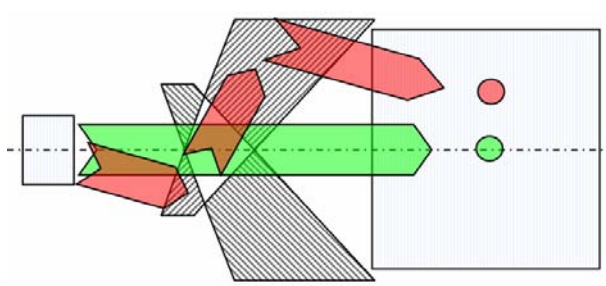

Fig. 7. Layout of the intermediate grating in an even method having only two first order diffractions. The green dot represents the gaze point at the center of FOV and the red dot at the vertical edge of FOV.

The beam representing the center of the FOV is propagating exactly in horizontal direction. The vertically expanding grating areas are small and the number of diffractions is mostly zero, i.e. the beam continues directly towards the out-coupling grating.

The beam from the in-coupling grating, that represents the upper part of the FOV, travels downwards, i.e. opposite to the gaze point on the out-coupling grating, as depicted in Fig. 7. The smaller grating area first flips the beam to the upper part and then the larger area grating redirects the beam correctly. These grating areas have the same conical orientation. The layout in Fig. 7. shows about the maximum areas of the vertically expanding gratings. Reducing especially the larger grating area can be used in optimizing the out-coupling light distribution.

The ray tracing simulation shows that the distribution of light at the out-coupling area is smoothened and that light is brought to the gaze position. A slight problem is that the small grating areas create some edge diffraction which affects to the sharpness at the high vertical angles. However, a proper design of the grating edges alleviates these problems. The center of image therefore is free from the edge diffraction of the vertical expansion.

4. Summary

The diffractive EPE revolutionizes the NED technology with very compact optical structure and high comfortableness. Its performance has been recently improved almost an order of magnitude from the basic concept using slanted gratings and novel diffractive grating designs. The system is intrinsically of a see through type and it can be easily converted to a stereoscopic display. The thin film solution hails the known color and angular problems. With the novel vertical expansion method the light can be gathered to the gaze direction improving significantly the brightness of the system. The convergence and focus of the system is initially at infinity but it is expected that both of these parameters can be tuned to 1-2 m distance. Therefore the EPE based NED is almost the “Mission Impossible” type VRD.

5. References

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