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Toshiteru Nakamura, Yuzuru Takashima, "Physical and geometrical hybrid design of two-layer and depth-chirped holographic image guide for see-through glass type head mounted display," Proc. SPIE 10757, Optical Data Storage 2018: Industrial Optical Devices and Systems, 107570D (14 September 2018); doi: 10.1117/12.2323239

SPIE.

Event: SPIE Optical Engineering + Applications, 2018, San Diego, California, United States

Physical and geometrical hybrid design of two-layer and depth-chirped holographic image guide for see-through glass type head mounted display

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ABSTRACT

We designed the image guide with discretely depth-chirped holographic grating for head mounted display to equalize luminance over the Field of View (FOV) and increase throughput. To reduce the time required to optimize depth-chirped pattern, the mathematical optical efficiency prediction method was devised. The design approach enables, rapid turnaround in design process and precise prediction of optical performance of image guide incorporated depth-chirped grating. Display performance of the depth-chirped image guide identified by the mathematical optimization was verified by the geometrical and physical hybrid optical simulation that the RCWA code is integrated to geometrical ray trace code via DLL to incorporate effects of the diffraction. As a results, the design exhibited 315 cd/m²/lm for the FOV (35° (H) x 20° (V)) and eye box size (±8.5 mm (H), ±6.5 mm (V)). The value of luminance was increased by 37% than unchirped image guide. Uniformity of luminance was further improved, from 33% to 47%. In conclusion, we made clear the effect of depth-chirped image guide to increasing the performance of the image guide.

Keywords: Head mounted display, image guide, depth-chirped, uniformity of luminance

1. INTRODUCTION

There is a growing demand for Head Mount Displays (HMDs) in consumer and enterprise applications¹⁻². One of the common scenarios in the enterprise application, HMDs provides a work support by Augmented Reality (AR) technology. For the small form-factor optics and see-through function, image guides incorporating holograms as an input/output beam combiner and a pupil expander has been developed and widely investigated³⁻⁸. The thin flat plate with holographic element are placed in front of eye and creates the virtual image, thus suitable for a small eyeglass-shaped HMD module.

Although the functionality of the holographic image guide appears simple at a glance, in reality designing holographic image guide involves a rather complex optimization process to achieve uniform luminance of the virtual image over substantially wide Field of View (FOV) while minimizing loss of light during guiding light. In this paper, we propose incorporating a discretely depth-chirped surface relief hologram to optimize local diffraction efficiency according to FOV position to increase luminance throughput and its uniformity over the FOV. The hologram area is divided into sub areas where diffraction efficiency is individually controllable for example by varying grating depth. In the design process, first, we devised mathematical model of ray propagation focusing on energy splitting upon interaction of the ray with discretely depth-chirped hologram. By taking into account number of interactions with holograms and optical rays, the model is solved for throughput efficiencies of the depth-chirped image guide while using the values of pre-calculated diffraction efficiency by Rigorous Couple Wave Analysis (RCWA). The design approach enables, rapid turnaround in design process and precise prediction of optical performance by using depth-chirped pattern. The geometric (non-sequential ray trace) and ray-physical optics (RCWA) hybrid simulation are conducted to validate the depth-chirped pattern identified by the mathematical solution. The hybrid simulator verifies that for FOV of 40°, uniformity of 47 % is feasible which improving throughput by factor of 37% compared to non-depth-chirped design.

2. MULTI-LAYER IMAGE GUIDE DESIGN

Figure 1 schematically depicts HMD optical system employing holographic elements at surface of the image guide. Generally three holographic elements are incorporated as surface relief gratings as Input, Vertical Expander (VE) and Output holograms⁴⁻⁷. Input hologram introduces signal light from an external optics such as projection lens with micro-display into the image guide. The VE hologram expands vertical direction of eye-box. Finally, the Output hologram expands horizontal direction of eye-box and emit signal light to observer's pupil. In this configuration, grating vectors of each holograms (K_{Input} , K_{VE} , K_{Output}) are arranged to satisfy the relationship: $K_{Input} + K_{VE} + K_{Output} = 0$ so that light from output hologram has k-vector has the same magnitude of the k-vector of input signal light. Thus, HMD user can see a virtual image in their view. Once input rays interact with Input hologram, 1st order diffraction on the Input hologram couples energy from air to guiding mode inside the glass slab. Inside the slab, the signal light propagates by total internal reflection (TIR). At the VE and Output hologram, similar process occurs. Light is redirected from VE (Output) hologram to Output hologram (Observer) by 1st order diffraction while part of the energy is further delivered towards edge of the VE (Output) hologram by the TIR of 0th order diffraction light.

Fig. 1 (color online). (a) Schematic of image guide; (b) Throughput optical system of HMD using image guide, and solid color lines represent optical ray from micro-display which are colored corresponded to each signal color.

In general, multiple image guides are needed to propagate wide wavelength (RGB spectrum) because using a single layer image guide is a challenge due to variation of diffraction angle over wavelength range. In the design for angle of incidence (AOI) of light inside the image guide, the AOI of the light has to be larger than TIR angle criteria, so that TIR angle has to be as minimum limit of AOI of the light. On the other hand, in theory, the maximum allowable AOI is less than 90 degrees, though in reality, < 80 degrees is a practical limit since light has to interact with VE and Output holograms multiple times. When blue and green light satisfy the required AOI range between TIR and 80° , red is difficult to satisfy the condition due to large AOI from large diffraction angle. To solve the problem, even higher $n_d > 2.2$ is required. Unfortunately, the value $n_d > 2.2$ exceeds n_d of typical optical glass material. Based on the analysis, two-layer image guide are designed to separate propagation layer by wavelength, which has an image guide designated for blue (B-image guide), and designated for red (R-image guide). Green light which is wavelength between red and blue propagate both image guides. High index material (S-LAH88, Ohara glass, $n_d = 1.91650$) is assumed as image guide material, and blazed or multi-level grating is feasible to fabricate by state of the art fabrication techniques⁹⁻¹⁰.

3. DESIGN OF DEPTH-CHIRPED IMAGE GUIDE

3.1 Overview of depth-chirped image guide

In case of the image guide as shown in Fig. 1, the image guide has common issue of uniformity of luminance at right and bottom side of FOV. This can be understood of the gradient of the luminance distribution schematically explained in Fig. 2. Signal ray forming left side of the image interacts hologram typically 10 or 20 times more than signal ray forming right side of the image, as a result, left side image loses luminance. In a similar way, upper side image loses luminance due to frequent interaction to the VE grating.

Fig. 2. Ray propagation process of signal light forming (a) left side image; (b) right side image.

To solve the problem of non-uniformity of the luminance over the FOV, we introduced depth-chirped grating to the image guide. In this design, the VE and Output grating are divided into multiple regions (sub-areas) having a different grating depth to control diffraction efficiency over the sub-areas (Fig. 3). At each of the sub areas grating depth is optimized to balance luminance over the FOV and increase overall optical throughput. Usually, HMD optical systems using the image guide involves both geometric and physical optics ray trajectory, and luminance of image is analyzed by geometrical optics while diffraction efficiency of holograms are incorporated there. The Rigorous Coupled-Wave Analysis (RCWA) method¹¹⁻¹³ is used to calculate diffraction efficiency of hologram. However, in the geometric and physical optical analysis of the image guide, so many diffraction rays have to be traced, and it causes longer calculation time, for example about 10 hours a condition. That means difficulty to identify the best-solution of depth-chirped pattern. To overcome the computational time issue, we develop rapid optimization method is described in detail in this section.

Fig. 3. Schematic of depth-chirped image guide.

3.2 Mathematical model for the image guide with depth-chirped sub hologram areas

We devised mathematical model of ray propagation focusing on energy splitting upon interaction of the ray with holograms for prediction of optical efficiency. A formulation of the developed optical efficiency prediction model considers critical factors for optical efficiency on the optical system from the light engine to user's pupil via image guide. Upon interaction of a ray to the Input hologram, a portion of power is taken away as a diffracted ray while rest of the power is preserved as a 0th order diffraction. The process is repeated while ray interacts multiple times with sub areas of VE and Output hologram where diffraction efficiency at time of interaction is different among sub-areas.

Fig. 4. Schematic of (a) light loss caused diffraction at back side Input hologram; (b) footprint of re-incident light at Input hologram; (c) fill factor of emitting ray from Output hologram.

With the aid of Fig. 4, the process is mathematically formulated to calculate optical efficiency of ray through B-image guide along single ray (f_B), and is given by,

$$f_B = \eta_{B-Input}(d, \lambda, \theta, \phi, T, 1^{st}) * (1 - \beta) \quad (1)$$

$$* \prod_{i=1}^n \eta_{B-VE}(d_i, \lambda, \theta, \phi, R, 0^{th})^{(m_{B-VE,i}-1)} * \eta_{B-VE}(d_{k_{VE}}, \lambda, \theta, \phi, R, 1^{st})$$

$$* \prod_{i=1}^n \eta_{B-Output}(d_i, \lambda, \theta, \phi, R, 0^{th})^{(m_{B-Output,i}-1)} * \eta_{B-Output}(d_{k_{Output}}, \lambda, \theta, \phi, T, 1^{st}) * \rho_{\lambda,B}$$

In Eqn. (1), diffraction efficiency of each hologram is denoted as

$$\eta_{NameofGrating}(d_i, \lambda, \theta, \phi, Mode, DiffOrder) \quad (2)$$

the efficiency is a function of grating depth d , wavelength λ , AOI of θ , and direction of grating ϕ of grating groove measured from horizontal direction of field of view. The subscripts “*Mode*” is either *T*: Transmission, or *R*: Reflection, “*DiffOrder*” denotes order of diffraction, “*Name of Grating*” specifies kind of HOE such as B-VE is a VE hologram for Blue, and “*i*” is an index of sub areas counted in ascending manner along ray propagation direction. The term in first line of Eqn. (1) denotes efficiency of ray when it interacts with B-Input hologram and coupled to B-image guide via 1st order diffraction in transmission. As described in Fig. 5 (a), light loss due to re-incident to the back side of Input grating itself (β) is given by Eqn. (3)

$$\beta = \sum_{i=1}^n \left[\left(\frac{1}{2} - \frac{1}{\pi} \sin^{-1} \frac{2(S_i - L)}{D} - \frac{2}{\pi D} (S_i - L) \cos \left(\sin^{-1} \frac{2(S_i - L)}{D} \right) \right) * \left(\eta_{Input}(d, \lambda, \theta, \phi, R, 0^{th})^{i-1} - \eta_{Input}(d, \lambda, \theta, \phi, R, 0^{th})^i \right) \right] \quad (3)$$

where ray traveling distance per a TIR is S , and half size of Input hologram is L as shown in Fig. 5a and Fig. 5b.

The term in second line of Eqn. (1) calculates efficiency of single ray while it propagates on B-VE hologram area. Number of incidence to VE grating area for single ray is denoted as Eqn. (4)

$$m_{Name of grating, i} \quad (4)$$

The subscripts “*Name of Grating*” specifies kind of HOE such as B-VE is a VE hologram for Blue, and “*i*” is an index of sub areas. The subscript “ k_{VE} ” in Eqn. (1) indicates the sub area couples the ray to diffract toward to Output hologram, and its value varies with FOV.

The term in third line of Eqn. (1) denotes efficiency of ray when it interacts with B-Output hologram. In this line, the calculation incorporates reflection efficiency of 0th order on B-Output, transmission diffraction efficiency of 1st order on B-Output to emit the ray toward to the eye pupil, and the subscript “ k_{Output} ” in Eqn. (1) indicates the sub area couples the ray to diffract toward to eye pupil, and its value varies with FOV. As mentioned above, the signal ray while reflecting in the image guide encounters VE and Output hologram again multiple times and it determine ray density at output hologram as a function of propagation angle (or correspondingly, function of FOV) is considered. (Fig. 5c). The fill factor of emitting ray ($\rho_{\lambda, Layer}$) is calculated by Eqn. (5)

$$\rho_{\lambda, Layer} = \sum_{-m}^m \sum_{-n}^n \left[2D^2 \cos^{-1} \left(\frac{d_{mn}}{2D} \right) - \frac{1}{2} d_{mn} \sqrt{4D^2 - d_{mn}^2} \right] \quad (5)$$

where the exit pupil radius of projection lens is R , distance to adjacent emitting ray is d (Fig. 5(b)). The subscript index of $\rho_{\lambda, Layer}$ specifies λ is wavelength, and Layer such as B is an image guide layer for Blue.

Similarly, optical efficiency of ray through R-image guide along single ray (f_R) is given by Eqn. (6)

$$f_R = \eta_{B-Input}(d, \lambda, \theta, \phi, T, 0^{th}) * \eta_{R-Input}(d, \lambda, \theta, \phi, T, 1^{st}) * (1 - \beta) \quad (6)$$

$$* \prod_{i=1}^n \eta_{R-VE}(d_i, \lambda, \theta, \phi, R, 0^{th})^{(m_{R-VE,i}-1)} * \eta_{R-VE}(d_{k_{VE}}, \lambda, \theta, \phi, R, 1^{st})$$

$$* \prod_{i=1}^n \eta_{R-Output}(d_i, \lambda, \theta, \phi, R, 0^{th})^{(m_{R-Output,i}-1)} * \eta_{R-Output}(d_{k_{Output}}, \lambda, \theta, \phi, T, 1^{st}) * \eta_{B-Output}(d_{k_{Output}}, \lambda, \theta, \phi, T, 0^{th}) * \rho_{\lambda,R}$$

As signal ray goes to R-image guide transmit Input hologram of B-image guide, multi-layer structure is modeled in a following way. The transmitted 0th order diffraction efficiency of B-image guide at Input hologram is considered (Fig.

5a). Similarly, transmitted 0th order diffraction efficiency of B-image guide at Output hologram is considered because signal ray come from R-image guide transmit Output hologram of B-image guide (Fig. 5b).

Fig. 5. Schematic of (a) light loss caused Input hologram of multi-layer structure; (b) light loss caused Input hologram of multi-layer structure.

Total optical efficiency of double layered image guide is given by Eqn. (7)

$$f_p = f_B + f_R \quad (7)$$

As a grating structure, a multi-level grating having 10 steps is assumed to approximate a blazed grating in this model. Diffraction efficiency is pre-calculated by RCWA as a function of AOI and wavelength, and polarization. In this model, diffraction efficiency is used as an average of p-polarized light and s-polarized light, so that the model has reprehensive grating depth diffraction efficiency η . If there is no matching condition data of grating depth, the model refers to the value of the adjacent data point and uses linear interpolation to estimate the diffraction efficiency of interest.

Using built rapid prediction method for optical efficiency, it is possible to conduct extensive search and optimize for depth-chirped grating within a practical time range. In this paper, the image guide model is assumed under condition of that FOV is 40 degrees (35° (H) x 20° (V)) and eye-box size is H: ± 8.5 mm, V: ± 6.5 mm. Size of VE and Output area are determined under consideration of eye-box size. Diameter of eye pupil is set 4mm, and thickness of image guide is set 1 mm a layer. Wavelength is considered 455 nm, 520 nm, and 615 nm. The optical efficiency is estimated in 9 points which are within the center of each block of 3 x 3 grid across the virtual image. The merit function for optimization evaluates uniformity of luminance along horizontal or vertical direction, and depth-chirped pattern is optimized to minimize a value of the merit function. VE/output area is divided to 5 sub-areas and optimized each area's grating depth. Since shallow or deep grating grooves are difficult to manufacture, grating depth of image guide are optimized from 40 nm to 200nm, and optical efficiency is constrained to exceed the efficiency of un-chirped image guide.

4. PHYSICAL AND GEOMETRIC ANALYSIS

4.1 Physical and geometric hybrid simulation

To evaluate accurately the image guide performance, the uniformity of luminance and power throughput of the discretely depth-chirped image guide which is identified by the developed optimization method is further simulated in the geometrical and physical hybrid optics simulator. The RCWA¹¹⁻¹³ code is integrated to geometrical ray trace code (Zemax) to incorporate effects of the diffraction angle, grating depth, and polarization. In Fig. 6, a block diagram of the hybrid simulator is shown. In HMDs, light is guided through glass substrate by TIR and interacts with holograms multiple times. Upon each interaction with for example output coupling hologram, light is partially diffracted towards eye box. The hologram-light interaction condition are not unique, but varies over the field of view mainly due to variation of AOI and polarization state of ray with respect to grating vector of hologram, grating depth, and wavelength. To simulate such sequence of interactions a Dynamic Link Library (DLL) is developed to link RCWA code to geometrical ray trace code. As depicted in Fig. 6 DLL interfaces Zemax to lookup data created by RCWA code based on geometrical diffraction direction, polarization and electric field amplitude.

Fig. 6. Block diagram of physical and geometrical hybrid simulator

4.2 Analysis result of un-chirped image guide

The performance of optimized image guides are verified by analysis by the above mentioned hybrid simulator. Light source is assumed as spectrum of the LEDs (Osram LCG H9RM, LEBA Q7WM) which has wide wavelength spectrum. The throughput optical system is shown as Fig. 1, and geometrical dimension of the image guide (thickness, hologram size, pupil size) is set same condition in the mentioned above.

First, the image guide having un-chirped (normal) hologram grating structure is analyzed. The results of luminance distribution of virtual image on each color shown in Fig. 7. In the graphs, the result of relative luminance at the each 9 evaluation points based on luminance of image center are shown. Virtual image of FOV is 35° (H) $\times$ 20° (V), and uniformity (Uniformity is determined by minimum relative luminance value at 9 evaluation points of screen based on evaluation point “5” in fig. 7g). and throughput is 33%, and 230 cd/m^2 , respectively. However, right side and bottom side of image tend to be high luminance and left side and upper side of image tend to be low luminance as mentioned in section 2.

Luminance of virtual image by un-chirped image guide is calculated under condition of that each RGB LED light emitting duty is adjusted to display white color whose color coordinate is $x=0.31$, $y=0.34$ at center of virtual image. When luminous flux of signal light at the exit pupil of light engine is 1 lm , luminance of image center of un-chirped image guide is 230 cd/m^2 .

Fig. 7. Simulation results of un-chirped image guide. Luminance distribution of virtual image on (a) blue LED; (b) green LED; (c) red LED; and (d) Relative luminance of each evaluation point based on image center on (d) blue LED; (e) green LED; and (f) red LED; (g) Evaluation point on the virtual image.

4.3 Analysis result of depth-chirped image guide

The simulation results of virtual image with image guide which is depth-chirped only in Output hologram (VE hologram is un-chirped.) is shown in Fig. 8. Luminance reaches to $280 \text{ cd/m}^2/\text{lm}$ ($x=0.31$, $y=0.34$) with depth chirping grating at Output hologram when the light engine outputting 1 lm luminous flux as signal light at exit pupil, and luminance is increased by 22% than normal image guide structure. There is a change in luminance distribution using Output hologram's depth-chirped structure but uniformity of luminance is 35% that is almost same value as un-chirped image guide.

Fig. 8. Simulation results of depth-chirped image guide (VE is un-chirped). Luminance distribution of virtual image on (a) blue LED; (b) green LED; (c) red LED; Relative luminance of each evaluation point based on image center on (d) blue LED; (e) green LED; and (f) red LED.

Compared to previous analysis results, the design result of the image guide which is depth-chirped Output and VE hologram is shown in Fig. 9. The results shows that the Output and VE hologram's depth-chirped structure improves uniformity of luminance from 33% to 47%. Luminance at the image center reaches to 315 $\text{cd/m}^2/\text{lm}$ ($x=0.31$, $y=0.34$) when the light engine outputting 1 lm luminous flux as signal light at exit pupil. Luminance is increased by 37% than the un-chirped image guide according to reducing the light loss in propagation process by the depth-chirped image guide.

Fig. 9. Simulation results of depth-chirped image guide (VE, Output are depth-chirped). Luminance distribution of virtual image on (a) blue LED; (b) green LED; (c) red LED; Relative luminance of each evaluation point based on image center on (d) blue LED; (e) green LED; and (f) red LED.

Besides, considered actual grating characteristics calculated by RCWA has dependence of wavelength, AOI, groove direction and polarization. Also, actual grating has diffraction efficiency of higher diffraction order. These factors prevent to increase performance of image guide. To understand theoretical limit of the image guide through put, ideal grating which has only 0th and +1st order diffraction and no dependence of wavelength, AOI and polarization are incorporated to the optimization model and its ideal depth-chirped image guide model is evaluated in geometric and physical analysis. In the result of ideal depth-chirped imageguide, luminance of virtual image reaches to 560 $\text{cd/m}^2/\text{lm}$ ($x=0.31$, $y=0.34$) when the light engine outputting 1lm luminous flux as signal light at exit pupil.

Fig. 10. Simulation results of depth-chirped image guide incorporated ideal grating. Luminance distribution of virtual image on (a) blue LED; (b) green LED; (c) red LED; Relative luminance of each evaluation point based on image center (position #5) on (d) blue LED; (e) green LED; and (f) red LED.

Analysis results mentioned above by the hybrid simulator are tabulated in Table 1. In spite of the image guide which is depth-chirped only in Output hologram has an effect to increase optical throughput. Furthermore, the image guide which is depth-chirped in VE and Output hologram achieve higher performance for both of optical throughput and uniformity of luminance.

The proposed mathematical prediction method of optical efficiency for depth-chirped image guide reduces the time required to optimize grating depth of the image guide. The mathematical prediction method achieves to estimate optical efficiency for 1 or 2 seconds without tracing millions of optical rays instead of the geometrical and physical optical simulation it takes for about 10 hours to calculate virtual image. The depth-chirped image guide identified by the mathematical prediction method is verified by physical and geometric hybrid analysis that achieves to increase

luminance and uniformity of luminance than un-chirped image guide. The proposed method is able to be applied to a specific design for depth-chirped image guides.

On the other hand, depth-chirped image guide using actual RCWA grating characteristic achieves 56% luminance of theoretical limit. Theoretical result imply luminance of image guide would increase about twice from new designed image guide. Due to actual grating has dependence of wavelength, AOI, groove direction and polarization and diffraction efficiency for higher diffraction order, these factors prevent to increase performance of image guide.

For the image guide mass production process, nanoimprint lithography technology may be easier way with low cost high throughput. Its process requires lower refractive index of substrate for reasons to match refractive index of imprint resist for efficiency and spectral and AOI characteristics requirements. Incorporating three or more propagating layer to the image guide is going to be lower refractive index of the substrate, and multi-layer image guide will achieve higher uniformity of luminance.

Table 1. Analysis summary of optical performance of the image guides.

Image guide	Luminance (cd/m ² /lm)	Uniformity (%)
Un-chirped	230	33
Depth-chirped (Only Output hologram)	280	35
Depth-chirped (Output and VE hologram)	315	47
Depth-chirped (Ideal hologram)	560	55

5. CONCLUSIONS

In this study, we designed depth-chirped image guide to equalize luminance and increase throughput over the FOV. The proposed mathematical optical efficiency prediction method for depth-chirped image guide reduces the time required to optimize grating depth of the image guide. The design approach enables, rapid turnaround in design process and precise prediction of optical performance by using depth-chirped pattern. Display performance of the depth-chirped image guide identified by the mathematical optimization was verified by the geometrical and physical hybrid optical simulation that the RCWA code is integrated to geometrical ray trace code via DLL to incorporate effects of the diffraction. The design exhibits 315 cd/m²/lm for the FOV (35° (H) x 20° (V)) and eye box size (±8.5 mm (H), ±6.5 mm (V)). This value of luminance at center of image is increased by 37% than conventional un-chirped image guide. Uniformity of luminance is further improved, from 33% to 47%, by introducing depth-chirped grating. As a results of geometrical and physical optical analysis, we conclude that the depth-chirped image guide optimized by the developed prediction method effect to increase the performance of the image guide.

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