Volume-Holographic Multiplexed-Mirror Waveguide for Head-Mounted Display

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ABSTRACT

As a waveguide for a head mounted display, we propose a volume-holographic multiplexed-mirror waveguide, which could achieve high luminance efficiency, wide field of view and excellent transparency. We clearly demonstrate that high performance waveguide is achieved by the combination of multiplex-recorded hologram and broad wavelength light sources.

1 INTRODUCTION

There is a growing expectation for a head mounted display (HMD) that can display information in the user's view. In addition to consumer applications such as game or second display of a laptop, HMD is expected for business applications such as work support in factories and distribution warehouses. As key component of a thin and light HMD waveguide [1], a mirror array [2], a surface relief grating (SRG) [3] or a volume holographic grating (VHG) [4-12] are developed. In the VHG, there are several types such as a VHG with a lens function [4], three multiplexed holograms [5-7], three layers of holograms [8], a hybrid configuration of SRG and VHG [9, 10], and a liquid crystal polymer [11, 12]. However, in these conventional VHG, it was difficult to achieve both wide field of view (FoV) and high luminance (optical) efficiency due to the narrow Bragg selectivity. Fig. 1 summarizes the result of our simple survey of each waveguide. Note that this comparison only shows general characteristics and state-of-the-art technology is out of scope.

In this study, we investigated a new type of VHG, which we call volume-holographic multiplexed-mirror (VHM). The VHM waveguide is based on a photopolymer with thickness of several hundred micrometers that have been developed for holographic data storage [13, 14]. We have developed HMD optical unit with high optical efficiency, wide FoV, and excellent transparency by using the VHM waveguide as shown in Fig. 1.

	Optical efficiency	FoV	Transparency
Mirror array [2]	high	narrow	scattering
SRG [3]	low	wide	scattering
Conventional VHG [4-8]	low	narrow	clear
Proposed VHM	high	wide	clear

Fig. 1. Comparison of waveguides for HMD.

2 VOLUME-HOLOGRAPHIC MULTIPLEXED-MIRROR WAVEGUIDE

2.1 BASIC CONFIGURATION

The main role of waveguide for HMD is an output coupler for light propagating by total reflection. Fig. 2 shows three configurations of output coupler by a half mirror, a single volume hologram and a multiplexed volume hologram. In a half mirror type, light can be reflected regardless of the wavelength and the incident angle. On the other hand, in a single volume hologram, reflection (diffraction) is performed only when the wavelength and angle conditions satisfy the Bragg-match condition. Then, the Bragg-match condition is relaxed by reducing the thickness of the medium and increasing the refractive index modulation to diffract light in a wide angle range. A multiplexed volume holograms can reflect (diffract) light almost independently of angle and wavelength by the design described later, and can be used as an element similar to a half mirror.

As a waveguide for HMD, it is difficult to widen the visible area (eyebox) while being thin with a half mirror. With a single volume hologram, the eyebox can be widened while being thin, but it is difficult to achieve a wide FoV. On the other hand, multiplexed volume holograms can achieve all of thin, wide eyebox and wide FoV. Therefore, we have investigated a waveguide using a multiplexed volume hologram called as VHM for an output couplers.

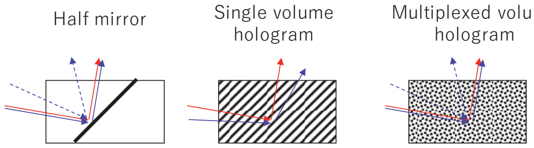

Fig. 2. Three type of output couplers.

Fig. 3 shows the configuration of a VHM waveguide. A light beam emitted from the projector propagates into the waveguide, and is diffracted by the multiplex-recorded volume-hologram. Then, the beam propagates to the eye. This waveguide can be created by using a volume type hologram, in which interference fringes having the same angle but different pitches are multiplex-recorded in the recording medium based on photopolymer. It was found that the inclination angle of the interference fringes of the hologram to the recording

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medium "θ_g" could be determined from the conditions such as FoV and the refractive index of the medium as follows:

$$\theta_g = \frac{1}{2}\left\{ \begin{array}{c} sin^{-1}\left(\frac{\sin(\theta_{fair})}{n}\right) + sin^{-1}\left(\frac{1}{n}\right) \\ +sin^{-1}\left(\frac{\sin\left(\frac{\theta_{FoV}}{2}\right)}{n}\right) + \alpha \end{array} \right\}, \qquad (1)$$

where, n is the refractive index of the cover glass outside the waveguide, θ_{fair} is the inclination angle of the waveguide to user's face, and θ_{FOV} is the angle of FoV in the air. α is the margin that is difference between the critical angle and the incident angle of the propagating beam with the smallest incident angle.

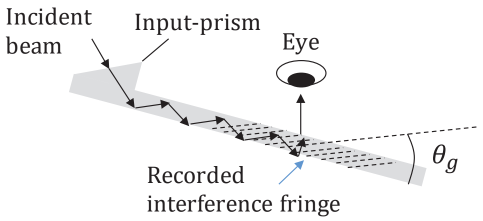


Fig. 3. Configuration of VHM waveguide.

2.2 MULTIPLEX-RECORDING METHOD

Next, the recording method for multiplexed holograms is explained. In the VHM waveguide, multiple holograms of plane waves with the same angle and different pitches are recorded. The holograms can be formed by recording interference fringes of two light beams on a photopolymer. The angle of the recording two beams are changed symmetrically to change the pitch of the interference fringes. Fig. 4 shows the configuration during recording and reproducing (diffraction of incident light). Here, when recording is performed with two beams tilted by θ_w with respect to the y-axis, the interference fringes can be made parallel to the x-z plane. Therefore, a VHM waveguide can be manufactured by installing the recording medium at an angle of θ_g with respect to the x-z plane so that the interference fringes are recorded at an angle of θ_g with respect to the recording medium.

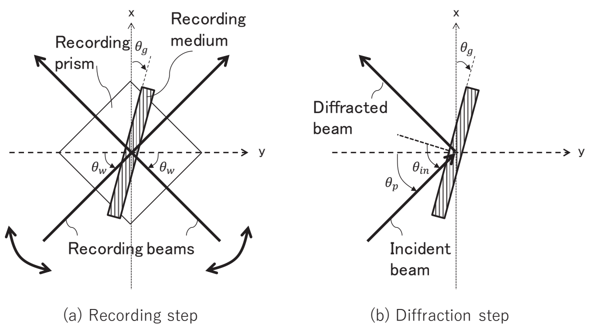


Fig. 4. Hologram recording and reconstruction setup for VHM.

2.3 DIFFRACTION CONDITION

Fig. 5 shows calculation results of the diffraction conditions of VHM using the equation as follows:

$$\lambda_p = \frac{cos(\theta_{in} - \theta_g)}{cos\theta_w}\lambda_w, \qquad (2)$$

where λ_w is the recording wavelength and λ_p is the reproduction wavelength. The calculation is performed by λ_w = 405 nm.

From Fig. 5, it is possible to confirm what wavelength of light is reproduced (diffracted) by the angle θ_{in} incident on the hologram recorded at a certain recording angle θ_w. For example, the white box in Fig. 5 represents the horizontal FoV angular range in the medium of 15 to 38 degrees (equivalent to FoV 35 degrees), where θ_w is 33 to 58 degrees. A VHM waveguide can be manufactured by multiplex-recording to cover this θ_w angular range.

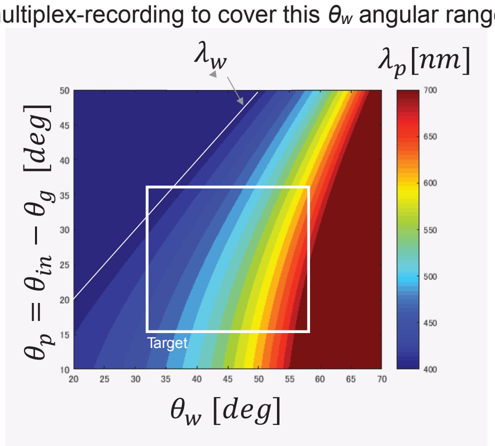


Fig. 5. Diffraction condition.

2.4 SIMULATION

The reproduced image of the VHM waveguide designed by the above calculation is simulated. Simulations were performed at the wavelengths of the two light sources: single wavelength and broad wavelength light source. A single wavelength assumes a light source with a narrow spectral width such as a laser display, and a broad wavelength light source assumes a light source with a broad spectral width such as a pseudo-white light source or RGB-LED (Light Emitting Diode).

By calculating the *k*-vectors (wave vectors) in the waveguide, we simulated the image viewed by the user wearing the HMD. Specifically, the hologram vector is obtained from the *k*-vector of the recording beams, calculated for the number of multiplex-recording times, and then the *k*-vector of the reproduction incident light is set from the reproduction spectrum and the reproduction angle. The diffraction efficiency of each wavelength was calculated, and the color and brightness of the image were obtained.

Fig. 6 shows the simulation results, where φ and θ are FoV in the vertical and horizontal directions, respectively (about 30deg × 35deg, light is guided in the horizontal direction). When input of a single wavelength, it is difficult to display the entire image, even with a single hologram or multiplex-recorded holograms. A line-shaped reproduction area is generated because Bragg match condition. On the other hand, with a light source of a broad wavelength, a single hologram displays images with different wavelength depending on the angle. Furthermore, when multiplex-recording is performed, the different wavelength are reproduced and added on user's retina, so that a white image can be seen. Therefore, when input of broad wavelength light sources and multiplex-recording is combined, a white image area is effectively generated. In this way, we found that it is effective to use the VHM waveguide with broad wavelength light sources.

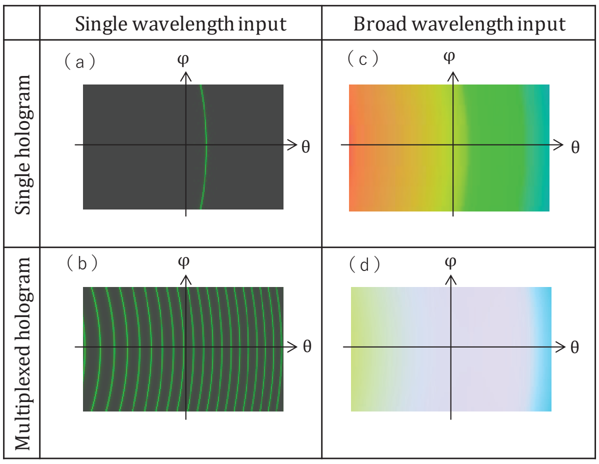


Fig. 6. Simulation results.

The design of the number of multiplex-recordings is explained. When manufacturing a VHM waveguide, the number of multiplex-recordings may be too much or too little. If the number of multiplex-recordings is small, color non-uniformity occurs in the images. Fig. 7 (a) shows the simulation results when the number of multiplex-recordings is changed. In addition, Fig. 7 (b) shows the evaluation results of image uniformity. Here, the uniformity is expressed in the CIE L*a*b* color space, and the reciprocal of the standard deviation value of the entire white image of the L* value is used for the uniformity. From this result, it can be seen that uniform images are possible by using more than about 30 multiplexes. On the other hand, the index M number (M/#) indicating the dynamic range of the modulation amount of the refractive index in the recording medium is limited, which limits the hologram diffraction efficiency and the number of multiplex-recordings. Considering the optical efficiency of the waveguide, which indicates how much of the incident light can be diffracted, there is a general relationship that the efficiency decreases as the number of multiplex-recordings increases as follows:

$$\mathrm{H}_{\mathrm{N,M}} = \frac{(M/\#)^2}{NM}. \tag{3}$$

When a hologram that has been recorded M times on a recording medium with a certain M/# until depleted, reproduction is performed with N incident rays (≒ N pixel images). The efficiency $\mathrm{H}_{\mathrm{N,M}}$ is inversely proportional to the number of incident rays N and the number of multiplex-recordings M. Therefore, in order to increase the optical efficiency, reduction of the number of multiplex-recordings is desirable. The uniformity of the image and the optical efficiency of the waveguide are in a trade-off relationship as shown in Fig. 7. Then, we compared prototypes with less and more than 30 multiplex-recordings as described in 3.2.

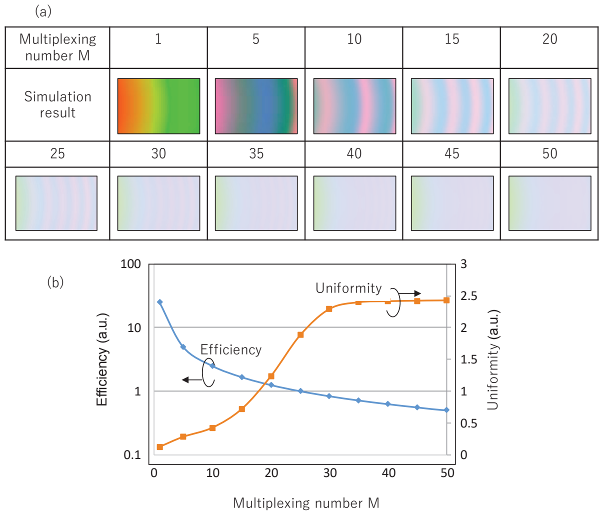


Fig. 7. Tradeoff between efficiency and uniformity
(a): Visible images in various multiplexing number.
(b): Relation between multiplexing number and efficiency or uniformity.

3 EXPERIMENTAL RESULTS

3.1 Color Image Display

Fig. 8 shows examples of the display images by the prototyped VHM waveguide. It can display full-color and bright images. All RGB full-color images can be displayed at FoV of more than 18 degrees. In addition, the displayed characters are visible without large blurring. In this prototype, the FoV is not so wide as 18 degrees. In the field utilization of work support, a too wide field of view is an obstacle to work while looking at information. As a result of verifying the optimum FOV (12 °, 18 °, 25 °, 45 °), it was 18 ° from the viewpoint of usability. There is no factor limiting FoV on the waveguide.

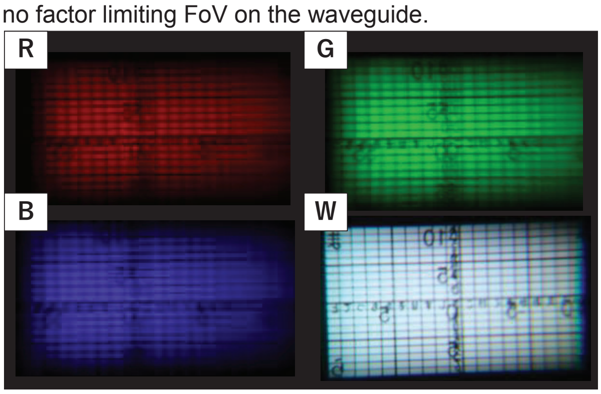
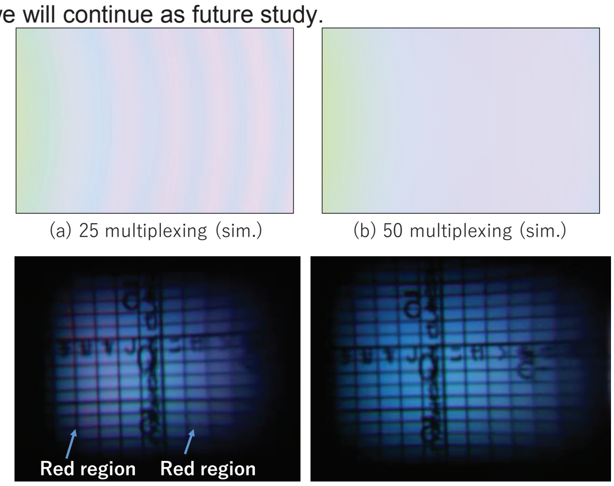


Fig. 8. Red, Green, Blue and White images (test chart) by VHM waveguide prototype.

3.2 Effect of Multiplexing Number

Next, Fig. 9 shows the difference depending on the number of multiplex recordings. Fig. 9 (a) and (b) are the simulation results (all white image input). The red line pattern is visible and color non-uniformity occurs with 25 multiplexing, but this pattern is not visible with 50 multiplexing. On the other hand, the same tendency can be confirmed in the experimental results Fig. 9 (c) and (d), and the red line pattern is visible and color non-uniformity occurs at 27 multiplex recording, but this pattern is not visible at 54 multiplex. Therefore, it was found that images with good color uniformity could be displayed by multiplexing about 50 times. In addition, since the optimization of the number of multiplex-recordings depends on the characteristics of the recording medium, we will continue as future study.



(a) 25 multiplexing (sim.) (b) 50 multiplexing (sim.)

(c) 27 multiplexing (exp.) (d) 54 multiplexing (exp.)

Fig. 9. Comparison of the different multiplexing numbers.

4 Conclusion

We have proposed an innovative waveguide technology for head mounted display called as “volume-holographic multiplexed-mirror (VHM)”. By newly combining dozens of holograms recorded on thick mediums and broad wavelength light sources, VHM waveguide achieves all of the excellent transparency, higher luminance efficiency and wider FoV than conventional VHG waveguide. Recently, a waveguide called as “skew-mirror” was proposed [15]. It is similar concept to VHM. However, we had investigated the detail of the VHM waveguide design and demonstrated the effectiveness of the waveguide with broad wavelength light sources in the first time as far as we know.

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