High See-Through and High Efficiency Waveguide for Head Mounted Displays and Waveguide Evaluations

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ABSTRACT

We have developed head mounted displays with high see-through property and high luminance which could be utilized outside safely without dimming glasses. We specified required performance threshold and developed beam-splitter-array waveguide to achieve the requirements. We also established versatile waveguide measurement method applicable to different-type waveguides.

1 INTRODUCTION

A see-through head mounted display (HMD), which presents data within user's field of vision, is a key device in an advanced information society with which the user can acquire necessary information in real time. Recently, many HMD applications have been proposed. A working supporting system which exploits digital technology is an example and expected to improve productivity at work site. For compatibility of user's safety and usability, the user should be able to see both HMD image and surrounding environment with an appropriate transmittance and luminance. In this paper, we have established specifications on transmittance and luminance for user's safety and usability. We then developed a waveguide for HMD and a sample of HMD which would be used under the sun. We have also established waveguide measurement methods which enabled us to compare multiple kinds of waveguides on the same basis.

2 SEE-THROUGH HEAD MOUNTED DISPLAYS

Fig. 1 shows a brief structure of a see-through HMD. The optical components of the HMD could be classified into two parts: a projector and a combiner. The image light from the projector is partially reflected to the user by the combiner, which is placed in front of the user's eye, whilst the light from environment partially transmits the combiner. Thus, the combiner has a functionality to superimpose the image of the HMD onto the surrounding outside world.

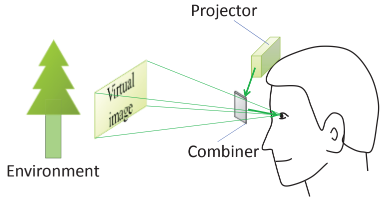


Fig. 1 See-through head mounted display

3 TARGET SPECIFICATIONS

3.1 Importance of Specifications on Transmittance and Luminance (Contrast Ratio)

The user of the see-through HMD would perform some activities with recognizing both HMD images and environments. An example is a case where the HMD is used in a working supporting system for construction, manufacturing, and infrastructure maintenance. The user would perform curing, sorting, and/or inspection works with referring and checking instructions shown by the HMD. Another example is a case where the HMD is used by a walker or a driver on a road. The user would work or drive a car by carefully watching the environment with referring some information shown by the HMD such as navigation.

For compatibility of user's safety and usability, the user should be able to see both HMD image and surrounding environment clearly. The ability to see the environment and the HMD image could be specified by the transmittance of the combiner and the contrast ratio of the luminance of HMD image relative to the luminance of environment. If the transmittance of the combiner is low, the user might not be able to see environment. Thus, the transmittance of the combiner shall be higher than a minimum criterion. If the luminance of image is too low, the user might not be able to see the image. On the other hand, if the luminance of image is too high, the user might be dazzled by the bright image. Thus, the luminance shall be within a minimum and maximum criterion.

3.2 Transmittance

In order to ensure that the user could see the outside environment clearly, the transmittance of the combiner shall be specified.

The transmittance of the combiner, T, is defined as

$$T = k \int_{\lambda_1}^{\lambda_2} T(\lambda)V(\lambda)P(\lambda)\mathrm{d}\lambda, \tag{1}$$

$$k = \frac{100}{\int_{\lambda_1}^{\lambda_2} V(\lambda)P(\lambda)\mathrm{d}\lambda}, \tag{2}$$

where $T(\lambda)$ is the spectral transmittance factor of the combiner, $V(\lambda)$ is the CIE standard photometric observer for photopic vision, $P(\lambda)$ is the spectral distribution of CIE standard illuminant such as A or D65 [1], λ_1 is the lower-limit wavelength of the visible spectrum range, and λ_2 is the upper-limit wavelength of the visible spectrum range. λ_1 shall be smaller than or equal to 380 nm, while λ_2 shall be larger than or equal to 780nm. Based on applications of HMDs, the CIE standard illuminant for the spectral distribution $P(\lambda)$ in Eq. (1) could be selected. For outside and inside usages, the CIE standard illuminants D65 and A would be preferred, respectively.

Table 1 Required performance threshold on transmittance

Case No.	Condition (use case)	Required transmittance
No. 1	The case where high see-through property is required without dimming effect, such as working supporting system where dimming effect is not preferred.	≥85%
No. 2	Outdoor usage, on road or when driving, at dusk or night.	≥75%
No. 3	Outdoor usage, on road or when driving, under sunlight.	≥8%

Table 1 shows the required performance threshold on transmittance of the combiner.

The case No. 1 refers to HMD applications where high transmittance is required and dimming effect is not intended. It is not related whether the HMD is used outside or inside. An example is working supporting system where dimming effect is not preferred in order to prevent degradation of environment recognition. This required performance threshold is based on that of safety glasses [2-4].

No. 2 and No. 3 refer to the cases where the HMD is used outside on road or by a driver of an automobile. These required performance thresholds are based on those of spectacle lenses [5].

3.3 Contrast Ratio (Luminance)

In order to ensure that the user could see the HMD image without dazzling, the contrast ratio of the luminance of HMD image relative to the luminance of environment shall be specified.

The light from environment partially transmits the combiner, while the image light from the projector partially goes out of the combiner. The contrast CR is defined as

$$CR=\frac{L_{\mathrm{vE}}+L_{\mathrm{vI}}}{L_{\mathrm{vE}}}, \quad (3)$$

where L_{vE} and L_{vI} show luminance of environment and image through the combiner, respectively.

Table 2 Required performance threshold on contrast ratio

	Required contrast ratio
Minimum	$CR \geq 1.15$
Preferable	$CR \geq 1.3$
Maximum	$CR \leq 4$

Table 2 shows the required performance threshold on contrast ratio. If the CR is lower than 1.15, the HMD image is not recognizable. In order to make the image visible for the user, the CR shall be larger than or equal to the minimum threshold 1.15 [6]. However, the CR of 1.3 is preferable for better recognition of HMD image [7]. In order to avoid dazzling, it is preferable that the CR is less than or equal to 4 [8].

An estimation of performance threshold on luminance with respect to environment illuminance is given by the following consideration. Let I_{E} be the illuminance of environment, that is, the illuminance on the object located at the background of HMD image. Assume that the object has the Lambertian diffusion profile and the reflectance factor is R_{obj}. Assume that the normal vector of the HMD image is equivalent to that of the object. Let T_{C} be the transmittance of the combiner. The luminance of environment L_{vE} is given by

$$L_{\mathrm{vE}} = \frac{I_{\mathrm{E}}}{\pi} R_{\mathrm{obj}} T_{\mathrm{C}}. \quad (4)$$

Thus, the required performance threshold on luminance L_{vI} is given by

$$L_{\mathrm{vI}} = (CR-1)L_{\mathrm{vE}} = (CR-1)\frac{I_{\mathrm{E}}}{\pi} R_{\mathrm{obj}} T_{\mathrm{C}}. \quad (5)$$

3.4 Target Specifications of HMD

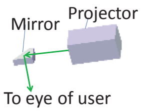
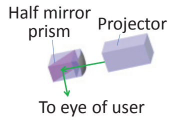
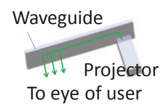
We performed HMD optical requirement adjustments to be used outside. The most severe case would be an application where the HMD is utilized under the sun in a working supporting system such as for construction, manufacturing, and infrastructure maintenance. The user should be able to see both HMD image and surrounding environment without any dimming glasses in order to carry out operations and to guarantee safety. Thus, the compatibility of high luminance and high transmittance is important.

By referring to the required performance thresholds shown in Table 1 and Table 2, we have set the target specification that the transmittance is higher than or equal to 85% and the contrast ratio is larger than or equal to 1.15. By considering that the maximum illuminance outside is about 100,000 lx and the object located at the background of HMD image is a white wall with reflectance 65%, the required minimum luminance of HMD image is 2,600 cd/m^2 when the transmittance is 85%.

4 BEAM SPLITTER ARRAY WAVEGUIDE

Table 3 shows several approaches to achieve see-through HMDs. In the pupil-splitting, a small mirror is placed in front of the eye. For see-through property, the height of the mirror is set to be smaller than the diameter of the iris of the eye. In the prism method, a prism with non-zero transmittance is utilized. Although the user could recognize both environment and the HMD image in both cases, the compatibility of large field of view (FoV), see-through property, and small-size optics is not achievable. To achieve the compatibility, we selected the waveguide method in which image light is transmitted within the waveguide by total internal reflection (TIR).

Table 3 Optical methods of see-through HMD

	Pupil-splitting method	Prism method	Waveguide method
Setup			
See-through	✓	✓	✓
Large FoV		✓	✓
Small size	✓		✓
Efficiency	✓	✓	

It would be a common understanding that a weak point of the waveguide method is efficiency. By considering HMDs are used outside, we must overcome it. Thus, we developed the beam-splitter-array (BSA) waveguide, which has advantages in high efficiency, high see-through property, small size, and high uniformity of image.

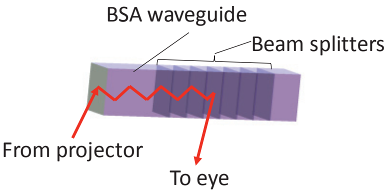


Fig. 2 Beam splitter array waveguide

Fig. 2 shows the BSA waveguide. The image light from a projector enters the waveguide through the input surface and transmits in it by TIR. The waveguide contains multiple parallel beam splitters. The light reflected by a beam splitter goes out of the waveguide. The user can see the image by perceiving the light from the waveguide. The multiple beam splitters have a functionality to expand the eye-box, which is the area where the user can see the image even when the user's eye is moved relative to the waveguide, because the light goes out of the waveguide every time it is reflected by the beam splitters.

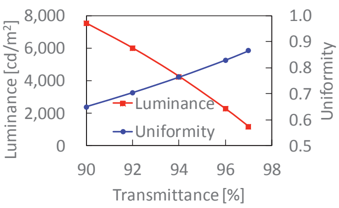


Fig. 3 Dependence of luminance on transmittance

The parameters of the waveguide: material, thickness, angle of beam splitters, the number of beam splitters, distance between nearest-neighbor beam splitters and transmittance of beam splitters; are carefully optimized by ray trace simulations because they are complexly related to efficiency, see-through property, image quality, eye-box size, the luminance uniformity over eye-box, weight and cost. Fig. 4 shows several simulation results. Higher transmittance leads to higher see-through property; however, luminance is decreased because light usage efficiency becomes lower. On the contrary, lower transmittance leads to higher luminance; however, the see-through property and luminance uniformity over eye-box U_s, the ratio between minimum and maximum luminance over eye-box, are degraded. We optimized the transmittance of beam splitters by considering the following points: the target specifications of transmittance and luminance are achieved, and U_s >70% which is the criteria that the user might not recognize luminance change. Especially, we focused on an ability to achieve higher luminance because it would enable users to see HMD image outside even in backlight conditions, or to extend HMD usage time because the same luminance is acquired by lower power consumption. These reflect opinions of users from PoC.

5 MEASUREMENT METHODS OF WAVEGUIDES

Although waveguides are key devices for next generation see-through HMDs, an appropriate evaluation method for waveguides is not established. In this development, we established versatile evaluation methods for waveguides which would be applied to evaluation of different type waveguides.

5.1 Transmittance

In order to evaluate see-through property, transmittance factor of the waveguide should be measured. Fig. 4 shows the measurement setup. Light from a xenon lamp was collimated by a lens to measure the transmittance per direction. The waveguide was set on a rotation stage and the incident angle was changed from 0 to 60 degrees. The light which transmitted through the waveguide was detected by an integrating sphere. The spectrum of the detected light was analyzed.

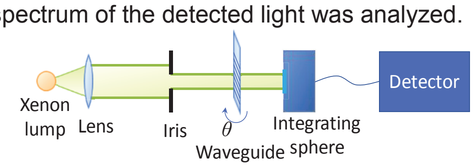


Fig. 4 Measurement setup of transmittance

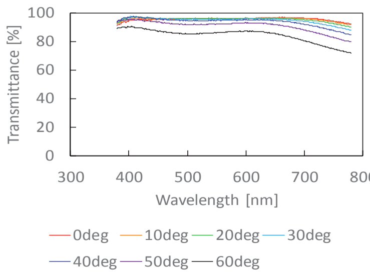


Fig. 5 Measurement result of transmittance

Fig. 5 shows the measurement result of transmittance factor on the BSA waveguide. By referring to Eq. (1) and Eq. (2), the transmittance was calculated. In the calculation, we have used the spectral distribution of CIE standard illuminant D65, $\lambda_1 = 380$ nm and $\lambda_2 = 780$ nm. We got 94% for the averaging from $\theta = 0°$ to $\theta = 60°$.

To evaluate color uniformity of see-through property, the non-uniformity of transmittance NU_T was calculated.

$$NU_T = \frac{\sigma_\lambda[T(\lambda)V(\lambda)P(\lambda)]}{E_\lambda[T(\lambda)V(\lambda)P(\lambda)]}, \quad (6)$$

where $E_\lambda[f(\lambda)]$ and $\sigma_\lambda[f(\lambda)]$ show the average and the standard deviation of $f(\lambda)$ over wavelength λ, respectively. We got 0.3% for the averaging from $\theta = 0°$ to $\theta = 60°$. The measurement result shows that the BSA waveguide has high see-through property: high transmittance and flat transmittance spectrum.

5.2 Luminance Efficiency

In order to evaluate light transmission efficiency, the luminance efficiency should be measured. Light image from a projector was input to the waveguide (Fig. 6). The luminous flux I of the projector was measured in advance. The luminance L of the virtual image shown via the waveguide was measured by a luminance meter. The luminance efficiency (η_L) was calculated by $\eta_L = L / I$. We got 13,000 cd/m^2/lm. The measurement result shows that the BSA has high light transmission efficiency.

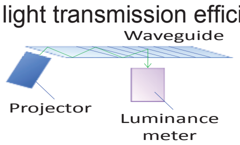


Fig. 6 Measurement setup of luminance efficiency

5.3 Transmission Spectrum

In order to evaluate color fidelity of transmitted image light, light transmission spectrum was measured. Light from a xenon lamp was collimated by a lens (Fig. 7). The light was input to the input surface of the waveguide. The light which exited from the waveguide was detected by an integrating sphere and its spectrum was analyzed.

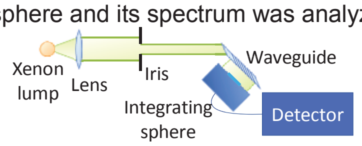


Fig. 7 Measurement setup of luminance efficiency

Fig. 8 shows the measurement result on the BSA waveguide. The data were normalized so that the peak was equal to one. The non-uniformity of light transmission spectrum was calculated by Eq. (6) and we got 0.3%. The measurement result shows that the color fidelity of light transmission is high in the BSA waveguide.

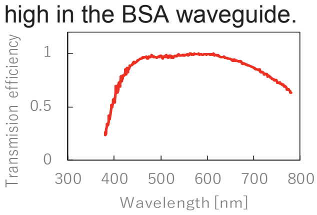


Fig. 8 Measurement result of transmission spectrum

6 PROTOTYPE

We made an HMD prototype with the BSA waveguide. By utilizing the BSA waveguide with high see-through property and high luminance efficiency, we got transmittance 94%, luminance 4,800 cd/m^2, and thus luminance contrast ratio 1.25 under the sun. They showed that our HMD satisfies the target specifications and has sufficient performance to be used outside.

7 CONCLUSIONS

We have specified required performance threshold on see-through HMDs. By considering user's safety and usability, transmittance of combiner and luminance contrast ratio was specified. The required performance thresholds we have specified are general and they can be referenced as specifications for see-through HMDs.

Although it would be a common understanding that waveguides have low optical efficiency, we have developed a BSA waveguide which have advantages in high see-through property and high luminance. We have also established versatile measurement methods for waveguides which could be used to compare different types of waveguides quantitively.

By utilizing the BSA waveguide, we have made a prototype of HMD with high transmittance 94% and high luminance 4,800 cd/m^2, and thus luminance contrast ratio 1.25 under the sun. With these advantages, our HMD is suitable for usage outside including applications of working supporting systems where dimming effect is not preferred, and the HMD is used under the sun. The ability to achieve high luminance would enable users to see HMD image outside even in backlight conditions, or to extend HMD usage time because the same luminance is acquired by lower power consumption. By combined with suitable application systems, our HMD will be a key component of working supporting systems which would be accepted in the working fields.

8 ACKNOWLEDGEMENTS

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REFERENCES

[1] ISO 11664-2, "Colorimetry – Part 2: CIE standard illuminants," (2007).

[2] ISO 4007, "Personal protective equipment – Eye and face protection – Vocabulary," (2018).

[3] ISO 4849, "Personal eye-protectors – Specifications," (1981).

[4] ISO 4854, "Personal eye-protectors – Optical test methods," (1981).

[5] ISO 8980-3, "Ophthalmic optics – Uncut finished spectacle lenses – Part 3: Transmittance specifications and test methods," (2013).

[6] K. W. Gish and L. Steplin, "Human Factors Aspects of Using Head Up Displays in Automobiles: A Review of the Literature," National Highway Traffic Safety Administration, DOT HS 808 320 (1995).

[7] C. R. Spitzer, "The Avionics Handbook," CRC Press (2001).

[8] Z. Qin, F. Lin, Y. Huang and H. D. Shieh, "Maximal Acceptable Ghost Images for Designing a Legible Windshield-Type Vehicle Head-Up Display," IEEE Photonics Journal 9, 7000812 (2017).